DISTRIBUTION AND ECOLOGY OF EXOTIC PLANTS IN WRANGELL-ST. ELIAS NATIONAL PARK AND PRESERVE, ALASKA

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A

THESIS

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By

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Abstract

The distribution of exotic plants and site factors influencing their abundance on roads and trails were studied in Wrangell-St. Elias National Park and Preserve during the summer of 2003. Seventeen species of exotic plants were found in the park at 173 locations. The most common species (*Taraxacum officinale*, *Plantago major*) were present at all study sites, while some (*Trifolium* spp., *Bromus inermis*, *Leucanthemum vulgare*) were restricted to specific disturbance types and particular areas. Though sampling was limited to areas in which exotic plants were growing, percent cover of exotics was not a significant component of sample sites, and exotic species richness was low at all sampling locations at 1.42 species per m^2. Data were analyzed using ordination and multiple regression to determine variables most responsible in explaining variation in exotic plant communities. Statistically significant site variables correlated with percent cover of exotics included percent cover of vascular native plants, percent cover litter, and percent bare soil at most study sites. The importance of these variables indicates that the presence of exotic plants in Wrangell-St. Elias is closely linked to disturbance, and that the invasion of exotic plants is in the initial phases.

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Introduction and Literature Review

Exotic plants are a major threat to the conservation of natural resources. They are capable of altering nutrient and disturbance regimes, out competing native species for limited resources, and can change the structure and function of ecosystems through alteration of geophysical and geochemical processes (Ruesnik *et al.* 1995, Gordon 1998). In protected areas such as national parks, exotic plants threaten the biodiversity and genetic integrity of native flora (D'Antonio *et al.* 2001) and degrade habitat for resident wildlife (Trammell and Butler 1995).

The National Park Service (NPS) is mandated to manage against non-native plant invasions, both in their charter (United States Congress 1872) and by executive order (Clinton 1994). The NPS has long recognized the threat exotic species pose to the lands they manage, and have a strong policy regarding their control and management, allowing them to distinguish between natural invasions brought about by range expansion and deliberate or accidental introductions by humans (National Park Service 1996). In response to increasing threats to park resources from exotic plant invasion, the NPS has created 17 exotic plant management teams throughout the country whose sole purpose is to control and eradicate non-native plant species on NPS lands (National Park Service 2004).

In Alaska, the NPS has recognized the importance of control and management. The resource management plan for Denali National Park and Preserve recognizes exotic plants as a significant source of potential adverse impact on the natural resources of the park (Denali National Park and Preserve 1998) and states that eradication and control actions should proceed concurrent with research to better understand exotic plant ecology and elucidate potential control actions. However, the Alaska National Interest Lands Conservation Act (ANILCA), which added millions of acres and over a dozen new parks to the NPS system in Alaska, has no provisions to deal with the potential threat or management of exotic plants on these lands. No new amendments have been passed to recognize this threat. In addition, studies of the status and distribution of exotic plants species in Alaska are limited, and the factors affecting their establishment and spread in the state are poorly understood (Spencer 2001). A statewide survey of exotic plants in Alaska national parklands was begun in 2000 and will continue through 2005 (Densmore *et al.* 2001).

Compared to national parks in the contiguous United States, Alaskan parks are still relatively untouched by exotic plant invasion (Westbrooks 1998). Several factors have protected Alaska NPS units. The most important is climate. Circumboreal plants are adapted to a wide range of climatic conditions that many exotic plant species cannot tolerate. In addition, national parks in Alaska are still relatively free of man-made disturbances such as livestock grazing, wildfire suppression, and altered hydrology that encourage invasion. Alaska units still contain intact ecosystems with all of the key floral and faunal components, in addition to natural disturbance regimes (Densmore *et al.* 2001). Despite these protective factors, the threat of exotic plant invasion is increasing due to global warming and increases in disturbance-related construction, among others. Fortunately, the NPS has the opportunity to get a head start on exotic plant introduction in Alaska, but research and active management must begin now (Spencer 2001).

Wrangell-St. Elias National Park and Preserve (WRST) is an ideal place to study the invasion of exotic plant communities into Alaskan national parks. It is the only park in Alaska with two roads within its boundaries. These roads have no restrictions on the kinds of vehicles that can enter the park, or on the number of people who can drive into the park. In addition to the road system, numerous off-road vehicle (ORV) trails leading off of both roads allow visitors to reach remote areas of the park. There are also a number of remote backcountry cabins located in the more popular wilderness areas of WRST that receive consistent use by park visitors. The communities of Slana, Nabesna, McCarthy, and Chisana represent permanent and seasonal human habitation close to or within WRST. The presence of so many types of human disturbances within WRST makes it likely that the park will continue to be susceptible to the introduction and spread of exotic plant species. Therefore, WRST can serve as a model by which the success of exotic plant invasions can be assessed within NPS lands in Alaska.

My study was designed to address these questions: 1. What species have invaded roads and trails in WRST, 2. How are these species distributed within and among roads and trails? 3. What factors influence the community structure in areas where exotic plants are growing in WRST? Knowledge of the numbers and distribution of exotic plant species, as well as information on factors related to the composition of communities containing these species, is an important first step in formulating monitoring and management plans to control their spread in protected areas. Since large infestations of exotic plants have yet to occur within Alaska national parks, it is vital that resource managers have plans in place designed to control or eradicate the exotic species that are present before these invasions become ecologically and financially untenable.

Definitions

Exotic plants have been referred to as aliens, nonindigenous species, invasive species, noxious weeds, and many other names. Some of these words have been used interchangeably and have resulted in much confusion, even among botanists. In agricultural settings, weeds are plants that grow where people do not want them and are usually competitive and pernicious in nature (James *et al.* 1991). Noxious weeds are those that have been legally recognized as having adverse economic or health impacts, usually within an agricultural context (Westbrooks 1998). In protected areas such as national parks, exotic plants are defined as those species occurring within a given area as a result of human actions (National Park Service 1996). These species can have a range of effects within protected areas from displacement of native plant populations to large scale changes in the structure and function of ecosystems (Ruesnik et al. 1995, Gordon 1998). Because a species is not native to an area, does not mean that it is invasive. Exotic plants are often associated with areas of anthropogenic disturbance, with ranges limited to those areas with large amounts of repetitive human disruption (Beerling 1991, Hobbs and Humphries 1995, Kowarik 1995). Invasive species, however, are a subset of the exotic flora that are capable of invading intact natural habitats (Convention on Biological Diversity 2004). About 3% of all known plants are considered to be invasive (Westbrooks 1998), and these are the species of greatest concern to natural resource managers.

National parks in Alaska do not harbor invasive plant species. Exotic species that are present are limited to a small number of areas, usually roads, trails and other forms of linear disturbance (Densmore *et al.* 2001). It is this suite of plant species that were studied for this thesis.

Biological characteristics and competitive strategies of exotic plants

Many authors have attempted to understand the biological characteristics that make plant species invasive in order to stop the initial invasion of such species, and to minimize the financial costs of control (Goodwin *et al.* 1999). Others have attempted to predict the potential distribution of exotic plants based on environmental conditions (Bazzaz 1986, Despain *et al.* 2001, Steinmaus 2002) or life history characteristics (Williamson and Fitter 1996). An integration of all three approaches may help to predict those species with the greatest potential for adverse impacts on natural ecosystems.

As a result of several studies, there appears to be a small number of biological characteristics that can predict the level of impact a given exotic species will have on an environment. Rejmanek and Richardson (1996) found that the invasiveness of the genus *Pinus* could be predicted based on the mean seed mass, the length of the plants juvenile period and the mean interval between large seed crops. Short juvenile periods and short intervals between large seed crops result in early and consistent reproduction and rapid population growth. Small seed mass would result in larger seed production (Greene and Johnson 1994), better dispersal (Rydin and Borgegard 1991) and high relative growth rates of seedlings (Walters *et al.* 1993). Noble (1989) found that the ideal invader was a phenotypically plastic perennial capable of germinating in a wide range of physical conditions, with fast growth rates, early flowering and wide dispersal as a result of massive seed production. Goodwin *et al.* (1999) recognized three biological characteristics that could be used to predict the invasiveness of a wide range of introduced species: life form, stem height, and flowering period. In addition, the original range of a species was also an effective predictor of a species invasiveness. Williamson and Fritter (1996) found that native and exotic species in the British Isles could be differentiated from one another based on habitat characteristics (soil fertility and altitude), morphology, life history, and reproductive behavior. Propagule arrival rates and suitability of climatic conditions also have a profound impact on the successful establishment and spread of invading species (D'Antonio and Dudley 1995, Lonsdale 1999).

Other authors have used competitive theory to explain the success of specific exotic species. Callaway and Aschehoug (2000) argued that some invasive plants succeed because they bring unique mechanisms of competitive advantage such as allelopathy into natural plant communities. Daehler and Strong (1997) showed how hybridization between introduced and native species of the genus *Spartina* resulted in greater recruitment of hybrid varieties than native species. In this way, an exotic species acts as a threat to the genetic integrity of native plant communities through introgression. Schweitzer and Larson (1999) compared the morphological plasticity between an invasive and native species of *Lonicera* and found that differences in internode length, internode number, and shoot biomass explained the greater plant fitness of the invasive species compared to the native variety. The combination of inherent biological characteristics and competitive behavior by exotic plant species are resulting in the homogenization of the world's flora (Westbrooks 1998).

Ecological effects of exotic plant species

The invasion of native plant communities by exotic species can have subtle effects on plant distributions and biodiversity (Westbrooks 1998) and more profound effects on the structure and function of ecosystems through alterations of geochemical and geophysical processes (Gordon 1998). Exotic plant invasions can also have serious financial impacts. Economically, exotic species costs U.S. taxpayers an estimated $123 billion annually (Arnold and Anthony 2000), with an estimated $7 billion in agricultural losses alone (Babbitt 1998).

Trammel and Butler (1995) studied the effects of leafy spurge (*Euphorbia esula*) and other exotic plant species on the habitat use of resident ungulates in Theodore Roosevelt National Park, North Dakota. The use of infested habitats by resident wildlife was reduced by up to 83% compared to non-infested areas, and was attributed to lower forage production at infested sites. Lym and Messersmith (1987) reported that infestation by leafy spurge reduced carrying capacity of pastures for livestock by up to 75%. Exotic plant infestations can have profound effects on habitat quality through alterations of forage quality and through avoidance of infested sites by resident wildlife (Hein and Miller 1992).

Exotic plant invasions can also have serious effects on the physical structure of invaded habitats. Craig *et al*. (1978) found that Australian pine (*Casuarina equisetifolia*), modified the geomorphological processes of shoreline erosion, resulting in the reduction of beach width, and that this process of erosion was accelerated by the exclusion of soil-stabilizing grasses by this exotic species. Lonsdale *et al.* (1989) showed how catclaw (*Mimosa pigra*) has caused the accumulation of sediments and disruption of water movement in the waterways of Australia and Thailand, and Smith *et al.* (1992) demonstrated how torpedo grass (*Panicum repens*) modified water channels by stabilizing banks along riparian corridors.

Invading species can also have serious impacts on soil function, biochemistry and nutrient cycling. Ehrenfeld *et al.* (2001) studied the effects of two exotic plant species, barberry (*Berberis thunbergii*) and Japanese stilt grass (*Microstegium vimineum*), on soil properties of eastern deciduous forests. Soils beneath each exotic species had higher pH values and higher rates of nitrification and nitrogen mineralization than adjacent patches with the most common native understory shrub. These discrepancies were attributed to differences in the mineralization and immobilization capabilities of the exotic plant litter. Both exotic species were altering soil properties in such a way as to promote their own growth and suppress the growth of native vegetation. Scott *et al.* (2001) examined the impact of hawkweed (*Hieracium pratense*) on soil and ecosystem processes in tussock grasslands of New Zealand. This exotic plant increased total soil carbon and nitrogen, and lowered pH and mineral nitrogen relative to adjacent native vegetation. The species may outcompete native vegetation for mineral nitrogen, thereby making native plant reestablishment difficult and promoting the spread of this exotic. Evans *et al.* (2001) quantified changes in the nitrogen cycle that occurred following the establishment of downy brome (*Bromus tectorum*) in Canyonlands National Park, Utah. Invasion of

Bromus increased litter biomass, and litter of *Bromus* had significantly higher C:N ratios than native species. Large scale invasions by *Bromus tectorum* are causing the establishment of positive feedback mechanisms that decrease nitrogen availability and alter the species composition of invaded areas. Alterations of soil nutrient dynamics by exotic species have been found in many other areas of the world, from Hawaii (Mack *et al.* 2001) to South Africa (Witkowski 1991).

Some exotic species are capable of causing large-scale changes in disturbance regimes. In Hawaii, the invading perennial grasses *Andropogon virginicus* and *Schizachyrium condensatum* have caused both an increase in fire frequency (Smith and Tunison 1992) and intensity (Tunison 1995). In parts of the western U.S., exotic annual grasses including *Bromus tectorum*, *B. rubens*, and *Taeniatherum caput-medusae* have all caused increases in both fire frequency and intensity, with fires encouraging the growth of these exotic species, thereby promoting a positive feedback mechanism (Brown and Minnich 1986, Whisenant 1990, Young 1992, Brooks 1998). Alterations of disturbance regimes by exotic plant species are varied in their scale and intensity.

<u>Corridors and exotic plant invasion</u>

The major vectors for introduction of exotic plant species are roads and other forms of linear disturbance such as hiking or Off-Road Vehicle (ORV) trails (Pauchard and Alabek 2004). Changes in nutrient regimes, repeated disturbance of topsoil, and the constant influx of propagules from vehicles and pedestrians allow alien species to become established along these corridors (Schmidt 1989, Panetta and Hopkins 1991, Lonsdale and Lane 1994). Roadside edges often have higher diversity of exotic species than adjacent patches of vegetation (Ranney *et al.* 1981, Brothers and Spingarn 1992). As a result, these forms of disturbance may serve as starting points for the spread of exotic plants into undisturbed environments.

Wilcox (1989) found that a highway in New York State served as a migration route for purple loosestrife (*Lythrum salicaria*), and that highway improvements increased the ability of this species to migrate to new wetland sites. Zink *et al.* (1995) looked at the composition of vegetation along a pipeline corridor in southern California and found that the more labile litter of exotic annuals allowed increased mineralization along the corridor compared to the more recalcitrant litter of surrounding native vegetation. This, combined with higher levels of incoming solar radiation along the pipeline due to disturbance, was allowing exotic plants to persist and spread.

Roads can also serve as point source inputs of nutrients and propagules, which can in turn encourage the establishment and growth of exotic species. Greenburg *et al.* (1997) found that the clay and limerock substrates used in the construction of unpaved roads provided a medium that allowed the establishment and persistence of exotic plants in the Ocala National Forest in central Florida. Ullmann *et al.* (1995) found that differences in environmental variables such as elevation, soil acidity and rainfall differentiated the floristic composition of sites with native and exotic plants on roadside verges in southern New Zealand, and suggested that exotic plants had colonized all available niches in these areas. Cale and Hobbs (1991) studied the effects of soil nutrient status on roadside vegetation in Western Australia and found gradients of soil nutrients across road verges that corresponded to similar gradients in the cover and diversity of exotic species.

Several studies have shown a trend of decreasing cover and diversity of exotic plant species with increasing distance from disturbance corridors. Tyser and Worley (1992) examined the spread of alien plant species into grasslands adjacent to road and trail corridors in Glacier National Park, Montana. They found a consistent pattern of declining exotic species richness with increasing distance from roads, indicating that these species are associated with road and trail related disturbances. Amor and Stevens (1975) studied the spread of exotics off of an old roadside into sclerophyll forests in Australia. Again, the frequency of exotic plants declined with increasing distance from roads and was associated with a reduction in diffused light. Jesson *et al.* (2000) also documented a decrease in the numbers of non-native plant species with increasing distance from roadsides in Arthur's Pass National Park in New Zealand, and suggested that the spread of these species was being limited by dispersal factors.

Exotic plants in national parks

Although most invasions of exotic plants occur in areas with high levels of anthropogenic disturbance, there is mounting evidence that the relatively pristine environments of national parks are also susceptible to invasion (DeFerrari and Naiman 1994, Heckman 1999, Stohlgren *et al.* 1999). As of 1996, non-native plants infested an estimated seven million acres of National Park Service (NPS) lands, with approximately 4600 acres of new infestations occurring daily (NPS 1996).

Weaver *et al*. (2001) compared exotic species in early and late seral stages in Glacier National Park and Grand Teton National Park in Montana, and found a gradient of declining exotic species richness from grasslands and open forests to alpine and moist forests. This gradient was attributed to declines in resource availability and dispersal limitations. Pauchard and Alaback (2004) studied roadside alien plant communities in two national parks in southcentral Chile and their relationship to elevation, land use and landscape context. They found that alien species were moving into parks along road corridors, and that elevation and land use influenced this invasion process, suggesting that surrounding developed areas should be considered when developing conservation strategies for these reserves.

The presence of people in national parks often results in the observed patterns of exotic plant growth seen in many protected areas. Jesson *et al*. (2000) investigated the effects of human disturbance, dispersal, and plant competition on exotic plant invasion in Arthur's Pass National Park, New Zealand. Human disturbance in developed environments influenced exotic plant invasions by reducing competition, changing nutrient regimes, and by aiding in the dispersal of exotic plant seeds into the area. Lonsdale and Lane (1994) looked at the importance of tourist vehicles as vectors of weed seeds in Kakadu National Park, northern Australia. The number of seeds and the occurrence of weed seeds on tourist vehicles were unrelated to the abundance of weed species in the park, but those species that were found on vehicles were present at three times as many sites in the park as those species that did not. Allen and Hansen (1999) studied eleven campgrounds in Yellowstone National Park to determine the geography of ten exotic plant species adjacent to campgrounds. Exotic species were most abundant close to campground areas and declined with increasing distance from developed areas, suggesting that the repeated disturbance by people in campgrounds was creating a favorable environment for the persistence of exotic plants.

Much of the literature dealing with exotic plants on national parklands deals with assessing the status, numbers and extent of exotic plants within protected areas. This might range from annotated checklists and inventories of exotic species (Olmstead 1865, Lesica and Ahlenslager 1993, Randall 1995, Gounaris and Grubbs 2000), to threat assessments (Moore and Gerlach 2001) and descriptions of exotic plant management programs (Free et al. 1990, Olliff *et al.* 2001). These studies are useful for detecting the presence of newly arriving species within a preserve once the total population of exotic species is known for a given area. Much of the inventory and monitoring work currently being done on exotic plants in national parks is for this purpose.

Exotic plants in northern latitudes

Although there has been a plethora of research on the effects of exotic plant species in lower latitude regions, little work has been done in high latitude areas. The invasion of exotic plant species, particularly into arctic regions, is thought to be limited by a short growing season and low soil temperatures. (Bliss 1987). Wein *et al.* (1992) documented the status of exotic plants in Wood Buffalo National Park, Canada and found that the majority of these species were growing in human-disturbed sites such as roadsides and farmlands. Cody *et al.* (2000) carried out a monitoring program to evaluate the effects of an oil pipeline on the vegetation in the western Northwest Territories of

Canada. They recorded 34 species of alien vascular plants along the pipeline right-of-way, including the aggressive weedy grass *Bromus tectorum*. MacLellan and Stewart (1986) conducted floristic surveys along a high voltage transmission right-of-way in Manitoba, Canada. They documented weedy plant assemblages within the disturbed corridor that differed from undisturbed sites in both species composition and distribution, and stated that the right-of-way was acting as a conduit for the invasion of weedy species into previously unavailable northern habitats. Wilson (1989) documented the suppression of native grass species in southwest Manitoba, Canada by alien species introduced for revegetation. Alien species persisted for nearly a decade after introduction, and growth of native grasses continued to be suppressed.

In Alaska, many species of exotic vascular plants have been documented in areas of human disturbance. McKendrick (2002) documented 18 species of exotic plants growing within the right-of-way of the Trans-Alaska pipeline, with the first species appearing just 16 miles from the Arctic Ocean. Many species were purposely seeded for erosion control and have persisted for 25 years or more. Kubanis (1980) looked at the recolonization of plant species along the Dalton Haul Road in arctic Alaska and found that although exotic plants were present in very low numbers, they tended to persist over long periods of time, indicating that the number and extent of these species could increase with an amelioration in the climate. Forbes (1992) studied the effects of anthropogenic disturbance on the Steese Highway between Fairbanks and Circle, Alaska and discovered several introduced species far from the roadside that had persisted for more than thirty years; long after disturbance-related activities had ceased. Densmore *et* *al*. (2001) conducted surveys for exotic plants in several Alaska national park units and documented as many as 18 different species in some units. Continued surveys have documented the arrival of new exotic species into some Alaska parks since initial surveys began (McKee 2003).

Surveys have revealed both the most successful invaders and the species of most concern on NPS lands in Alaska. By far the most successful exotic plant species in Alaska has been common dandelion, *Taraxacum officinale*. This species is a perennial, with deep taproots that are difficult to remove completely. Plants can regenerate from pieces of the tap root and flowers can produce up to 2,000 wind-blown seeds that are widely dispersed. The species is also capable of producing fruit without being fertilized (Alaska Natural Heritage Program 2004). Because of its complex reproductive mechanisms, the taxonomy of *Taraxacum* is problematic. This genus is often grouped into a "complex" of many micro species and only specialists are capable of distinguishing between individual species (Hulten 1968). Due to its high reproductive capacity and its ability to thrive in a wide variety of habitats, it is not surprising that it is prevalent in so many national parks in Alaska. Recent surveys in Wrangell-St. Elias National Park have found this species spreading along natural disturbances in riparian zones (McKee 2003).

Two species found growing in Alaska parks are generating the most concern among park resource managers: narrow leaf hawksbeard (*Crepis tectorum*) and white sweetclover (*Melilotus alba*). *C. tectorum* is an annual that can grow up to 3 feet tall, with each plant capable of producing more than 49,000 seeds (Royer and Dickenson 1999). It can outcompete native seedlings for available resources and is also capable of invading into riparian areas (United States Department of Agriculture 2004). Once established in large numbers, it can be hard to eradicate and control efforts should be carried out as soon as possible on infested lands (Densmore *et al.* 2001). White sweetclover is a nitrogen fixing annual or biennial plant that may grow up to six feet tall. It rapidly colonizes nutrient poor waste places and can spread quickly along river corridors. It has already been found growing aggressively along some major rivers in both the interior and southeast panhandle of Alaska (United States Department of Agriculture 2004). Large populations of this species have been found growing in or around 4 national parks in Alaska (McKee 2004).

Methods of studying exotic plants

A review of the relevant literature reveals two overall methodologies for studying exotic plants: opportunistic surveys and systematic sampling. Much of the work done using opportunistic surveys has been for purposes of collecting baseline information on the floristic composition of disturbed sites where weeds are prevalent. Densmore *et al.* (2001) developed a standardized collection protocol for assessing the diversity and abundance of exotic plants in Alaska national parks. This methodology was further refined to allow the use of highly accurate Global Positioning System (GPS) units that included fields used to describe the composition, size, and severity of exotic plant infestations in a given area (McKee 2004). There are numerous other examples of opportunistic surveys for exotic plants in the literature (i.e. McLellan and Stewart 1986, Wein *et al.* 1992, Cody *et al.* 2000).

Systematic surveys for exotic species are the most common methodology. Pauchard and Alaback (2004) used 500 meter transects to evaluate the influence of elevation, land use, and landscape context on exotic plant species distribution and abundance in two national parks in southcentral Chile. Transects were located at each kilometer of the roads going into each park. Alien species abundance was recorded qualitatively and for each transect, the elevation and land use in the surrounding area was noted. The significance of elevation, land use, and the interaction of the two in explaining the variation in alien species richness was evaluated using multiple regression. The ordination technique, Detrended Correspondance Analysis (DCA), was used to detect gradients in alien species assemblages. Watkins *et al.* (2003) studied the effects of forest roads on understory plants in the Chequamegon National Forest in Wisconsin using square meter quadrats placed at varying distances from forest roads. At each plot, the percent cover of understory species was recorded, as well as site factors such as slope, aspect, bare ground and litter. They also used DCA to determine whether distinct understory plant communities existed. Exotic species were analyzed independently from other species to see whether roads facilitated exotic species invasion. Parendes and Jones (2000) examined the role of dispersal, light availability, and disturbance in explaining patterns of exotic plant species along roads and streams in western Oregon. They used transects to measure variables along roads and streams in the study area. The ordination technique, non-metric multidimensional scaling, was used to examine patterns of exotic species along transects because of the highly nonnormal nature of the data. Regression was then used to test hypotheses regarding the probability of exotic species occurring in a particular habitat type and under specific light levels. Data collection via sampling transects followed by ordination and regression analysis, is a common theme throughout much of the literature on exotic plants (i.e. Wester and Juvik 1983, Diaz *et al*. 1994, Ullmann *et al*. 1995, King and Buckney 2002).

Methods

Wrangell-St. Elias National Park and Preserve is located in the southeastern section of the Alaska mainland (Figure 1) and is the largest national park in the nation. The park contains four major mountain ranges and a diverse assemblage of vegetation types ranging from coastal Western Hemlock-Sitka Spruce Forest to Interior Highlands (Gallant *et al*. 1995). Climatic conditions are variable, with precipitation averaging 338 cm and temperatures from 15° C to -9° C in the coastal area at Yakutat, to 20 cm of precipitation and temperatures from 20° C to -25° C in the interior highlands near Slana (Cook and Roland 2002).

Study sites in WRST were limited to areas of current and historical human use. This included both the Nabesna and McCarthy roads, the Kennecott mine area, Bonanza Ridge and May Creek (Figure 2). More remote areas of the park, such as backcountry use cabins and airstrips, were also visited but were not sampled due to a lack of exotics. Two plots were also established along the Root Glacier trail outside of Kennecott, but were excluded from subsequent analysis because soil samples could not be obtained due to the rocky substrate present along the length of this trail

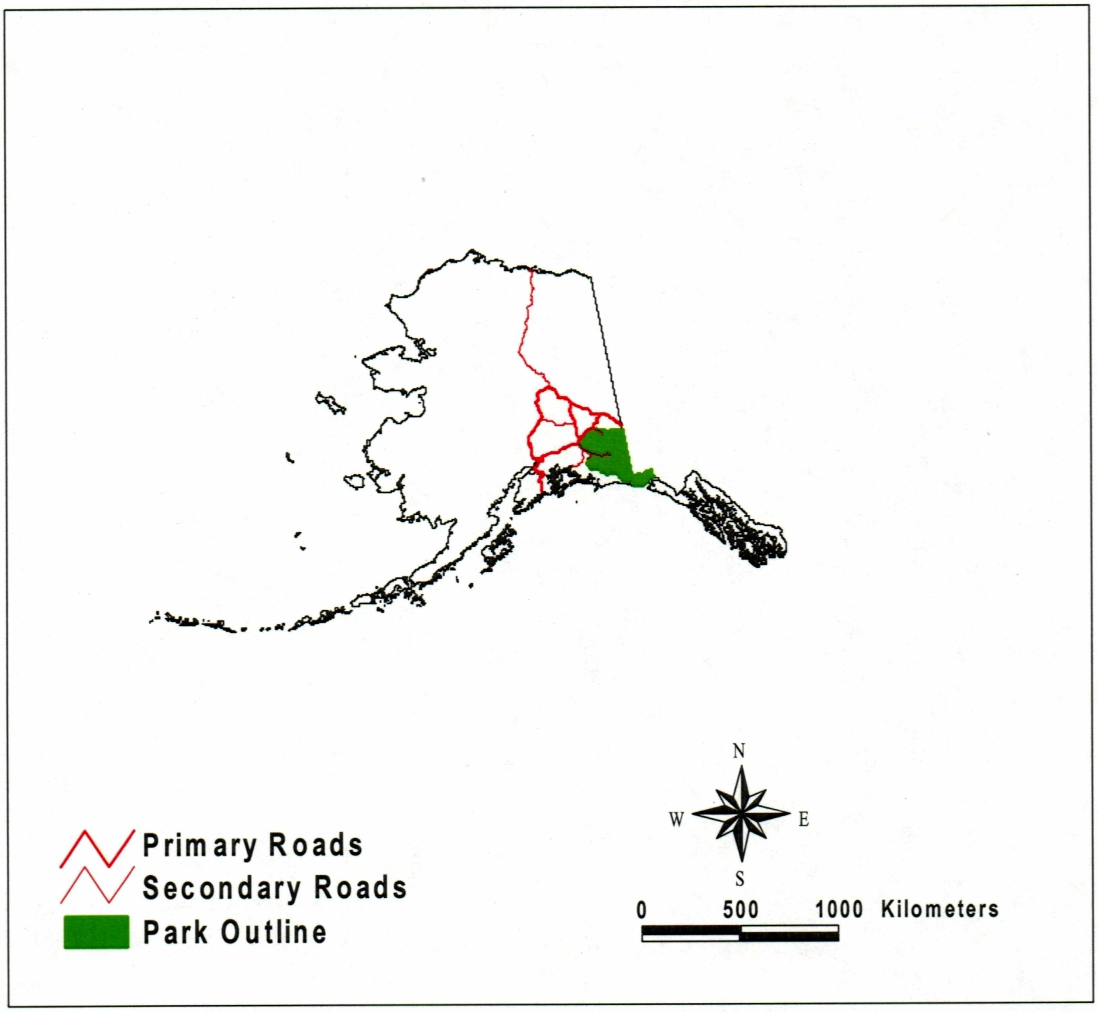

Figure 1. Location of Wrangell-St. Elias National Park and Preserve (WRST) within the state of Alaska.

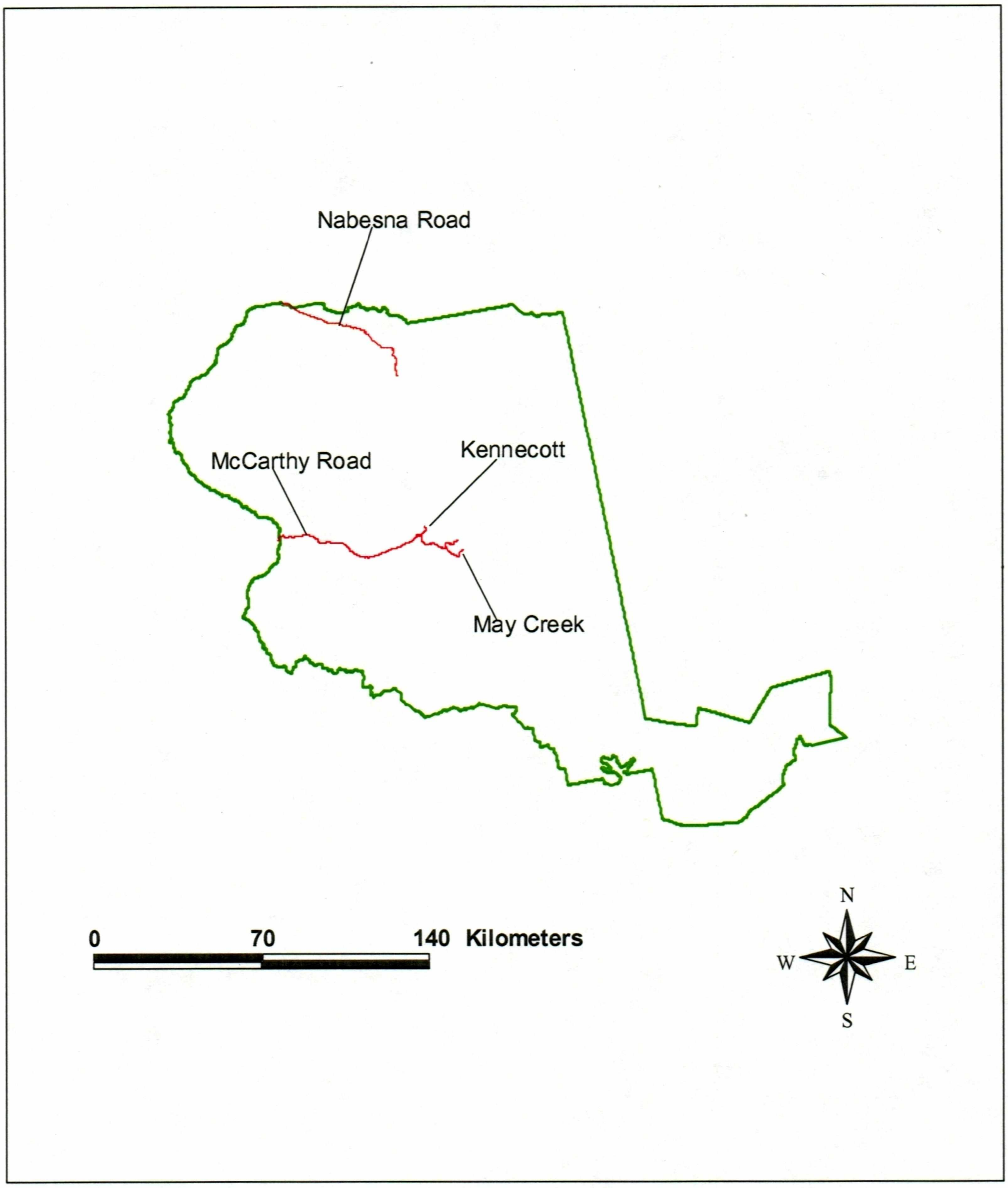

Figure 2. Location of study sites in Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Sampling Design

For the purposes of this study, the population was defined as all exotic species growing in disturbed sites in WRST. It was necessary to have a narrow sampling universe because exotic plants are confined to a limited set of conditions in WRST (i.e. human-disturbed areas). Therefore, randomly choosing where to sample within the park would have caused most exotic plant infestations to be missed just by chance.

Along each road, an initial survey of the area was conducted to inventory populations of exotic species. Locations of all exotics were recorded with GPS. The size of the exotic infestation was measured, and sampling took place within that area, usually along a linear corridor on a road or trailside. Trails were not surveyed prior to sampling due to time constraints. Instead, I walked as much of a given trail as possible within a day, and sampled my way back to the point of origin. At each site where exotic plants were growing, a square meter quadrat was placed at a randomly determined point along the length of the infestation and sampling took place within that area. After initial surveys along park roadsides, it became clear that the majority of exotic plant growth rarely extended more than 1 to 1.5 meters from the road edge into surrounding native vegetation. Consequently, the sampling frame was always placed to include exotic plants growing closest to the road and extending away from the road edge (Figure 3). The majority of exotic plants were sampled for each particular site, though some exotic plant species may have been excluded by this method of plot placement. In this manner, consistency of quadrat placement was maintained across all sample sites. Within the quadrat, percent cover of all exotic species was estimated. Site factors collected for each

Figure 3. Sampling quadrat placement, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

quadrat were: slope, aspect, elevation, percent cover of native vascular species, percent cover of native vascular and non-vascular species, percent cover of plant litter, and percent bare ground.

For each plot, soil samples were taken to a depth of 10cm in a randomly determined subsection of the sampling quadrat. Soils were air-dried and sieved prior to analysis. Soils were analyzed for pH, total nitrogen and carbon, and extractable phosphorus and potassium. Soil texture was determined using the Bouyocos-Hydrometer Method. All soil tests were performed at the UAF Agricultural and Forestry Experiment Station, Palmer Research Center, Palmer Alaska.

Data Analysis

Data were log $(x+1)$ transformed due to the highly skewed nature of the data and to meet assumptions of normality and homogeneity of variances. Transformations did not bring all variables in the dataset into complete agreement with assumptions of normality, but since the dataset was relatively large ($N > 100$), one can assume that the sampling distribution is normal, even if the distribution of the variables in the population are in question (StatSoft 2003).

Initial analysis was run using non-metric multidimensional scaling (NMS), with the software PC-ORD (Version 4, MjM Software 2002). Ordination serves as a method of data reduction when sampling within a multivariate environment. NMS is well suited for use with datasets that are nonnormal and because of this, is generally the most effective ordination procedure for use with community ecological data (McCune and Grace 2002, Tong 1989). NMS was performed using the quantitative version of

Sørensons' distance measure. It is an iterative process that searches for the best positions of *n* entities (plots) on *k* dimensions (axes) and seeks to minimize the "stress" in the *k*-dimensional space. Stress is a measure of the similarity between the distances in the original *n* x *p* data matrix and those in the reduced *k*-dimensional space (McCune and Grace 2002). In the case of my study, NMS was used as an exploratory method of investigation to identify the environmental variables most responsible for community structure in areas where exotic plants were growing. All ordinations were run after removal of outliers greater than two standard deviations from the average distances in the original data matrix. Monte Carlo tests were used to determine whether NMS was extracting stronger ordination axes than expected by chance (see Appendices 4-10). Selection of the appropriate number of axes for the ordination was determined by examining a NMS scree plot, which compares final stress of the ordination versus the number of dimensions.

Variables found to be important in explaining variation in the ordination axes were examined for statistical significance using multiple regression with percent cover of exotic plants as the response variable. Independent means tests were run on the data to compare the percent cover of exotic plants among and within disturbance types. All statistical tests were carried out using SPSS (SPSS Inc., Version 11.5 2002). Significance for all statistical tests was set at $\alpha = .05$.

Results

A total of 173 exotic plant sample locations were established within WRST (Appendix 1 and 2). Of these, 114 (66%) were located on the Nabesna and McCarthy

Roads, and 59 (34%) were located on the ORV/hiking trails in the park (Bonanza Ridge, May Creek, Kennecott). A total of 17 exotic plant species were found at the 173 sample locations (Table 1). By far the most common exotic plant species was common dandelion (*Taraxacum officinale officinale*), which was present in 65% of all sample plots. Common plantain (*Plantago major*) was present in 30% of all sample plots and Alsike clover (*Trifolium hybridum*) was present in 12% of plots. The other 15 exotic species identified were rare, together being present in 28% of all sampling locations (Figures 4-7).

Exotic species richness was low at all plots and across all sampling locations. Mean number of exotic species per plot was 1.42 per m^2 for the entire population. Mean exotic species richness ranged from a low of 1 species per plot on the Nabesna Road to 1.6 species per m^2 in Kennecott.

The number of exotic plant species at sample sites was highly variable, ranging from a low of one species at Bonanza Creek to nine species along the McCarthy Road. The most common exotic species *Taraxacum officinale officinale* and *Plantago major*, were common along both roads and sampled trails. Three species of clover, *Trifolium hybridum*, *T. repens*, and *T. pretense* were present at sample sites on the south side of the park (McCarthy Road, Kennecott, May Creek), but were absent on the Nabesna Road. Less common exotic species, such as prostrate knotweed (*Polygonum aviculare*) and common peppergrass (*Lepidium densiflorum*), were found on the McCarthy Road, but only along the first 10 miles. Two species of exotic grass, smooth bromegrass (*Bromus inermis*), and quackgrass (*Elymus repens*), were found on the McCarthy Road and

Table 1. Cover values of exotic species, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Species	Mean Percent Cover	Range	Frequency
Achillea millefolium	2.5	0.5-15	.06
Bromus inermis	27	3-15	.03
Chenopodium album	25	1-76	.02
Crepis tectorum	0.7	0.5-1	.02
Descurania sophia	9.3	1-25	.02
Elymus repens	0.7	0.5-1	.01
Lappula squarrosa	4.8	0.5-20	.03
Lepidium densiflorum	12	1-20	.02
Leucanthemum vulgare	33	30-35	.01
Matricaria discoidea	4.4	0.5-10	.03
Melilotus alba	35	35	.005
Plantago major	6.7	0.5-30	.30
Polygonum aviculare	11	3-22	.02
Taraxacum officinale officnale	12.4	0.5-60	.65
Trifolium hybridum	20.6	0.5-94	.12
Trifolium repens	3.3	1-6	.02
Trifolium pratense	23	23	.005

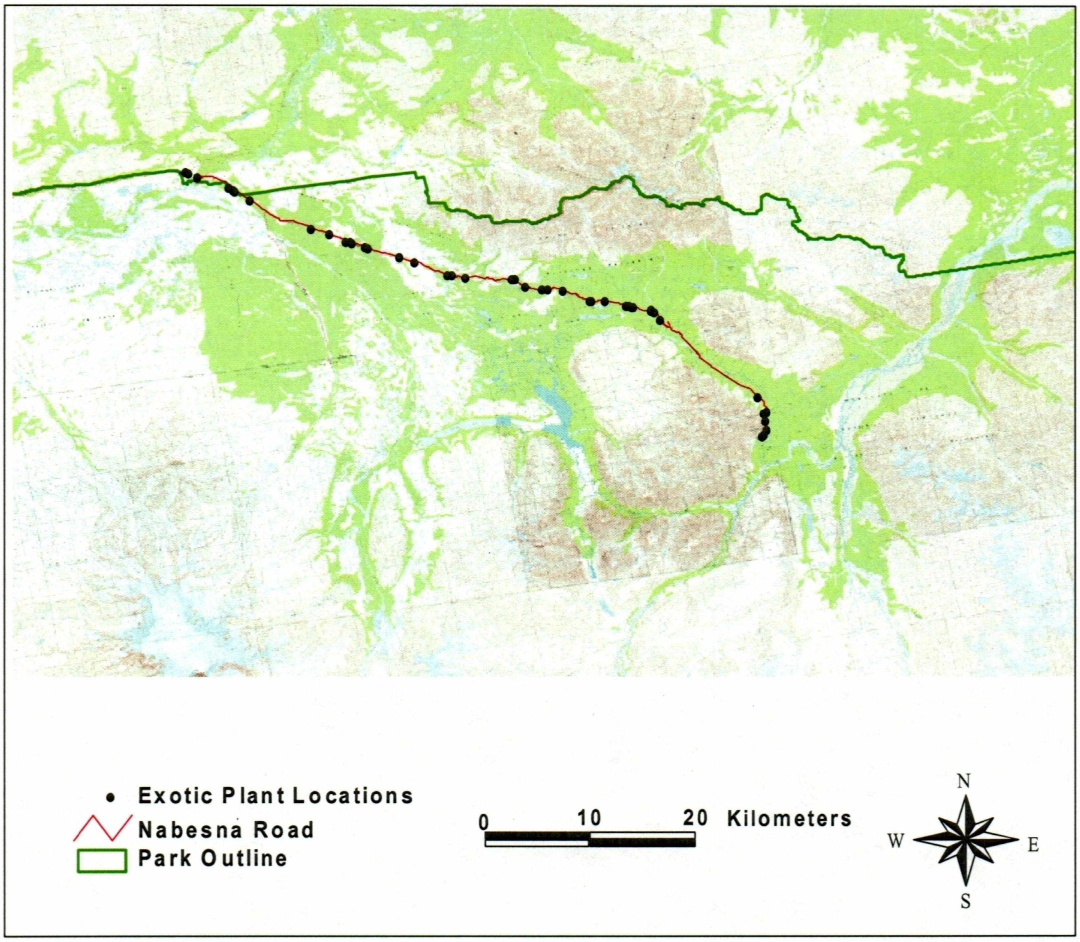

Figure 4. Exotic plant locations along the Nabesna Road, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

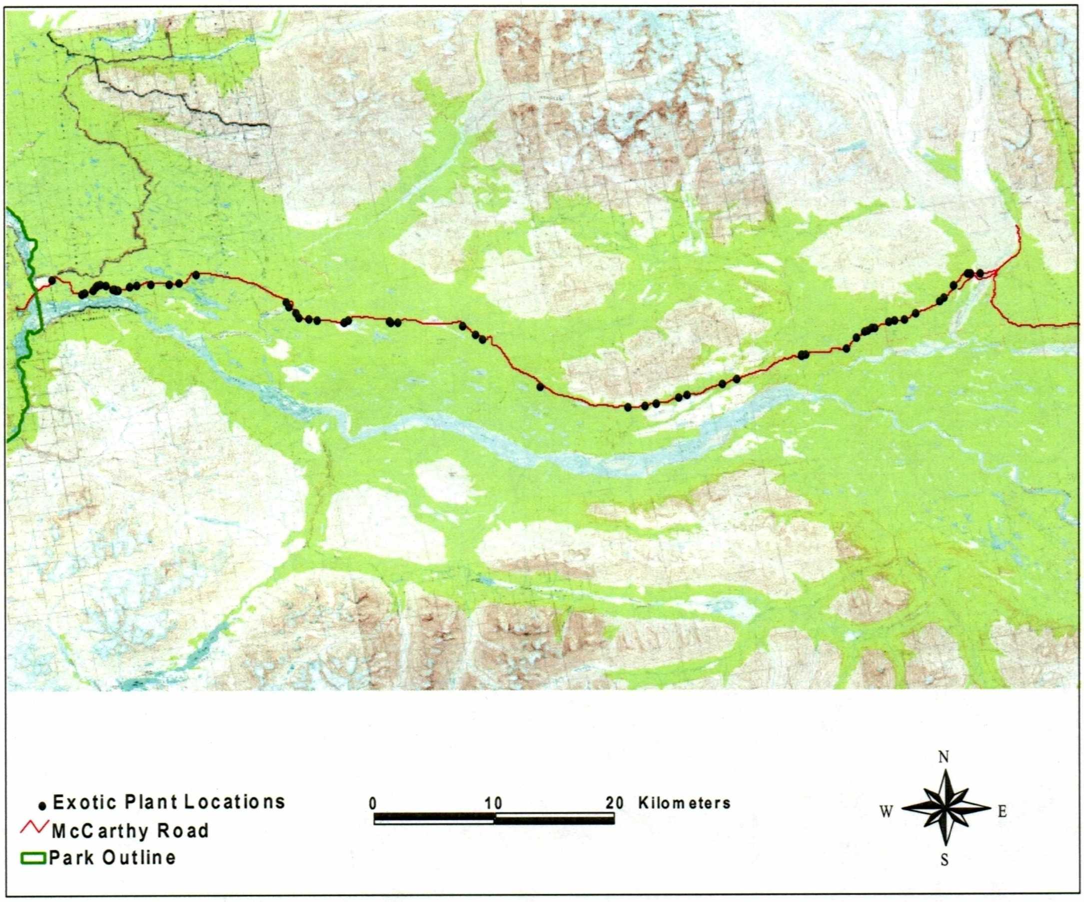

Figure 5. Exotic plant locations along the McCarthy Road, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

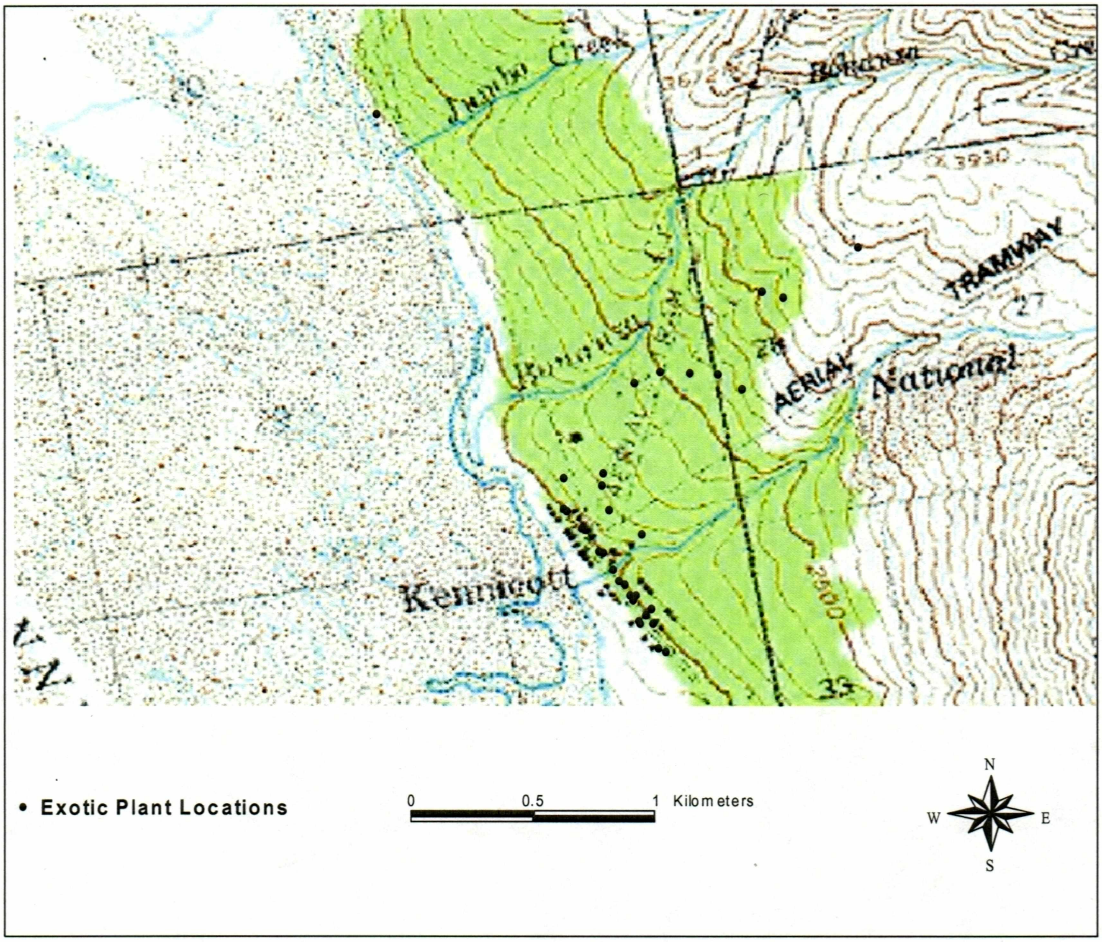

Figure 6. Exotic plant locations in the Kennecott Mine area, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

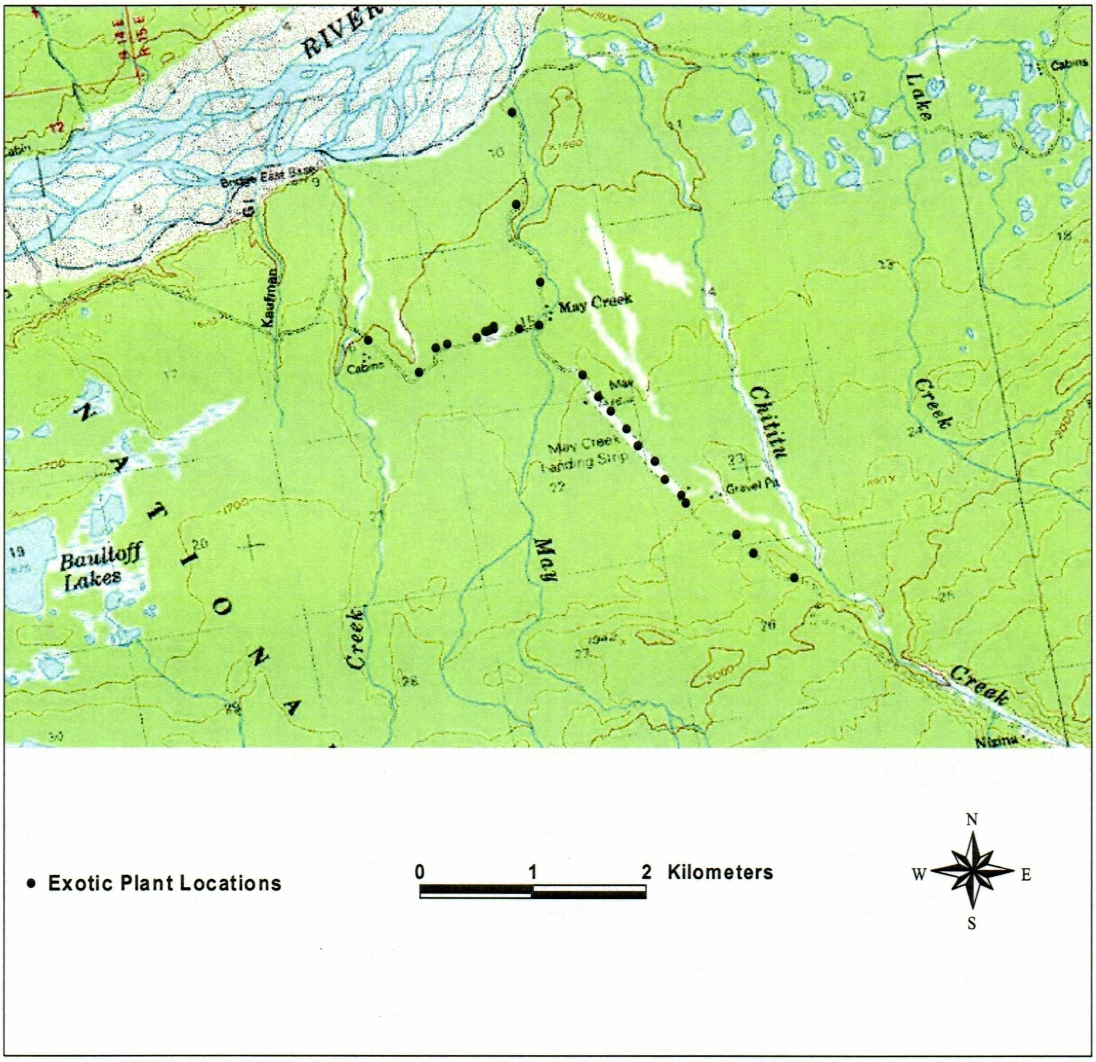

Figure 7. Exotic plant locations in the May Creek area, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

nowhere else. Oxe-eye daisy (*Leucanthemum vulgare*) and *Trifolium pratense* were present only along trails in the Kennecott Mine area.

Mean percent cover of exotic plants, vascular natives, non-vascular natives, litter and bare soil differed greatly from site to site. Percent of bare soil was greatest on the Nabesna and McCarthy roads (68% and 53% respectively) and was lowest on plots at May Creek (13%). Mean cover of exotics was greatest at Kennecott (31%) and lowest at May Creek (6%) (Figure 8). Average cover of vascular natives was highest at Bonanza Ridge (34%) and lowest on the Nabesna Road (16%). Mean cover of native non-vascular plants was low at all sample sites; ranging from a high of 8% at May Creek to a low of 0.18% along the Bonanza Ridge trail.

Data on soils revealed little variation between study sites for values of pH and soil texture, but values for major soil nutrients did differ between sites (Table 2). Specifically, values for phosphorus and potassium showed a differentiation between plots in the Kennecott area and those at May Creek. Plots in May Creek had high amounts of potassium, while plots in Kennecott had high amounts of phosphorus. There was little variation between the two roads in the park with respect to these two soil nutrients. Nitrogen content was highly variable between study sites. Plots at Kennecott were highly variable with respect to the major soil nutrients as, evident by the relatively high standard errors for these values.

Ordination

Ordination analysis was run on the full dataset, and also separately for data sets from the Nabesna and McCarthy Roads, and for each of the ORV/hiking trail sites. For

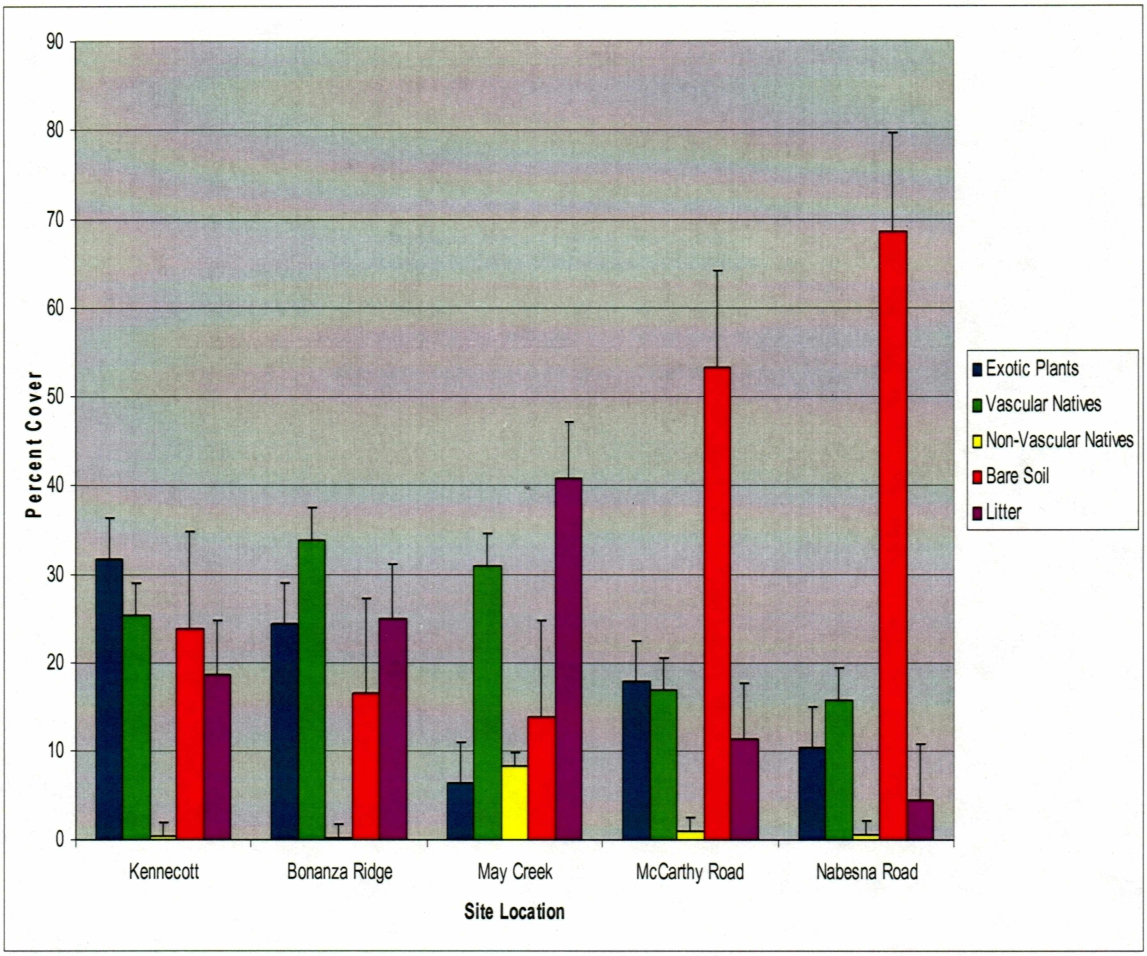

Figure 8. Mean cover of study plot variables, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Table 2. Soil variable values for each study site, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Study Site	Soil Variable	Mean	Standard Error	Range
Nabesna Road	pH	6.9	.07	5.5-7.9
	NH_4 (ppm)	6.5	0.5	1-16
	NO_3 (ppm)	8.6	1.1	1-6
	P (ppm)	11.4	.91	4-36
	K (ppm)	116.4	6.5	56-287
	% Carbon	2.7	.18	1-5.7
	% Nitrogen	.12	.01	.03-.28
	% Sand	73.6	1.4	40.8-89.1
	% Silt	16.5	1.1	4.8-33.6
	% Clay	9.9	.58	5.5-25.6
McCarthy Road				
	pH	7.5	.03	6.8-7.9
	NH_4 (ppm)	1.7	.11	1-4
	NO_3 (ppm)	4.2	.90	0.5-13
	P (ppm)	27.1	3.2	2-103
	K (ppm)	121.5	10.5	35-636
	% Carbon	4.4	.26	1.5-15.9
	% Nitrogen	.12	.01	.01-.82
	% Sand	65.7	1.7	35.6-88.4
	% Silt	22.6	1.3	4.8-53.3
	% Clay	11.6	.83	1.8-31.4
Bonanza Ridge				
	pH	6.6	.09	5.9-6.9
	NH_4 (ppm)	16.5	1.8	6-30
	NO_3 (ppm)	4.9	1.1	0.5-12
	P (ppm)	38.6	5.3	17-67
	K (ppm)	145.2	16.5	68-271
	% Carbon	5.6	.51	2.2-8.1
	% Nitrogen	.37	.04	.13-.63
	% Sand	64.4	2.6	51.2-79.2
	% Silt	23.3	1.2	12.6-32
	% Clay	12.3	.95	8-17.2

Table 2 Continued

Study Site	Soil Variable	Mean	Standard Error	Range
Kennecott	pH	6.9	.06	5.9-7.3
	NH_4 (ppm)	16.6	10.2	2-211
	NO_3 (ppm)	5.9	1.7	0.5-33
	P (ppm)	130	16.2	30-285
	K (ppm)	165.6	23.1	58-551
	% Carbon	7.4	.91	3.1-20.3
	% Nitrogen	.30	.04	.06-.76
	% Sand	70.2	2.2	44-87.4
	% Silt	19.3	1.9	4-45.8
	% Clay	10.5	.70	5.7-14.7
May Creek				
	pH	6.9	.05	6.4-7.4
	NH_4 (ppm)	6.1	.68	1-16
	NO_3 (ppm)	20.5	9.1	1-213
	P (ppm)	28.6	5.5	2-121
	K (ppm)	255.6	20.5	92-574
	% Carbon	5.5	.38	1.9-10.2
	% Nitrogen	.39	.03	0.7-.86
	% Sand	52.1	2.1	28.8-66.8
	% Silt	32.3	2.2	18.2-59.8
	% Clay	15.6	.59	9.3-20.4

purposes of analysis, all data on ORV/hiking trails were combined due to low sample sizes for each individual site. An ordination analysis was also run on the combined dataset for roads in WRST.

For the entire dataset (n = 173), plots were associated with percent bare soil, percent cover vascular natives, percent cover litter, potassium (ppm), and pH (Table 3). Weaker associations were also evident for percent silt and percent clay. The ordination procedure eliminated 11 other environmental variables from the original data matrix. NMS ordination (Figure 9) represented 92% of the variation in the dataset, with 58% loaded on axis 1, 18% on axis 2, and 16% on axis 3. Plots on the Nabesna Road (n = 51) were associated with percent bare soil, percent silt, potassium (ppm), and percent cover vascular natives (Table 4). A weaker association with phosphorus was evident for axis 1. The ordination procedure eliminated 12 other environmental variables from the original data matrix for this site. NMS ordination (Figure 10) accounted for 92% of the variation in the dataset, with 55% loaded on axis 1, 16% on axis 2, and 21% on axis 3.

Plots on the McCarthy Road (n = 63) were associated with percent cover vascular natives, percent bare soil, slope, potassium (ppm), phosphorus (ppm), and NH_4 (ppm) (Table 5). Weaker associations were evident for pH and percent sand. The ordination procedure eliminated 10 other environmental variables from the original data matrix for this site. NMS ordination (Figure 11) accounted for 94% of the variation in the dataset, with 59% loaded on axis 1, 14% on axis 2, and 21% on axis 3.

For the cumulative data on roads (n = 114), plots were associated with percent cover exotics, percent cover vascular natives, potassium (ppm), percent bare soil and

Table 3. Correlation coefficients of dominant matrix variables with ordination axes for the full dataset, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Variable	**Axis 1** r^2	**Axis 2** r^2	**Axis 3** r^2
% Cover Vascular Natives	.792	.056	.002
% Bare Soil	.150	.610	.050
% Cover Litter	.411	.010	.005
pH	.272	.330	.057
Potassium (ppm)	.155	.380	.208

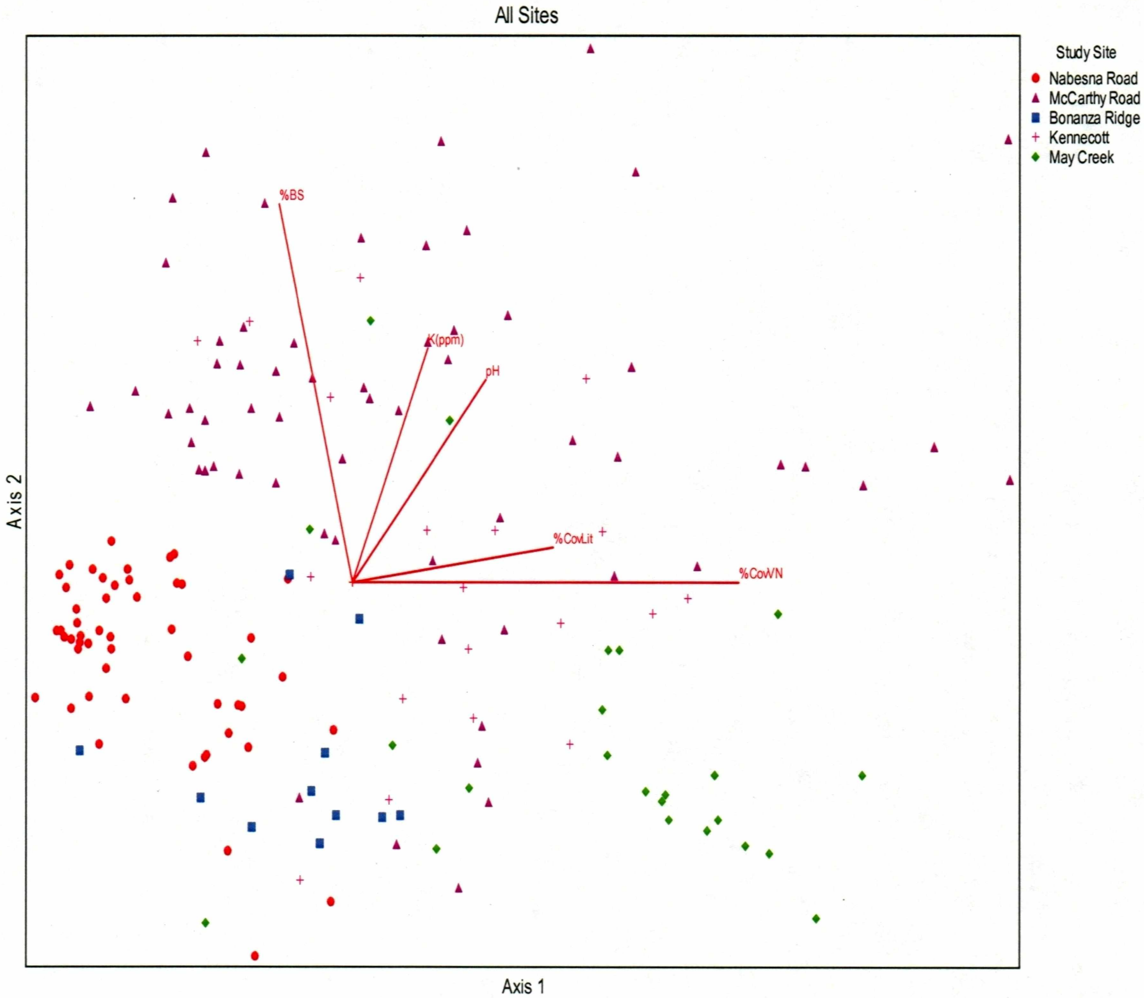

Figure 9. NMS ordination biplot for the full dataset, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Table 4. Correlation coefficients of dominant matrix variables with ordination axes for Nabesna Road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Variable	**Axis 1** **r^2**	**Axis 2** **r^2**	**Axis 3** **r^2**
% Cover Vascular Natives	.500	.050	.099
% Bare Soil	.436	.225	.360
Potassium (ppm)	.704	.001	.145
% Silt	.004	.137	.415

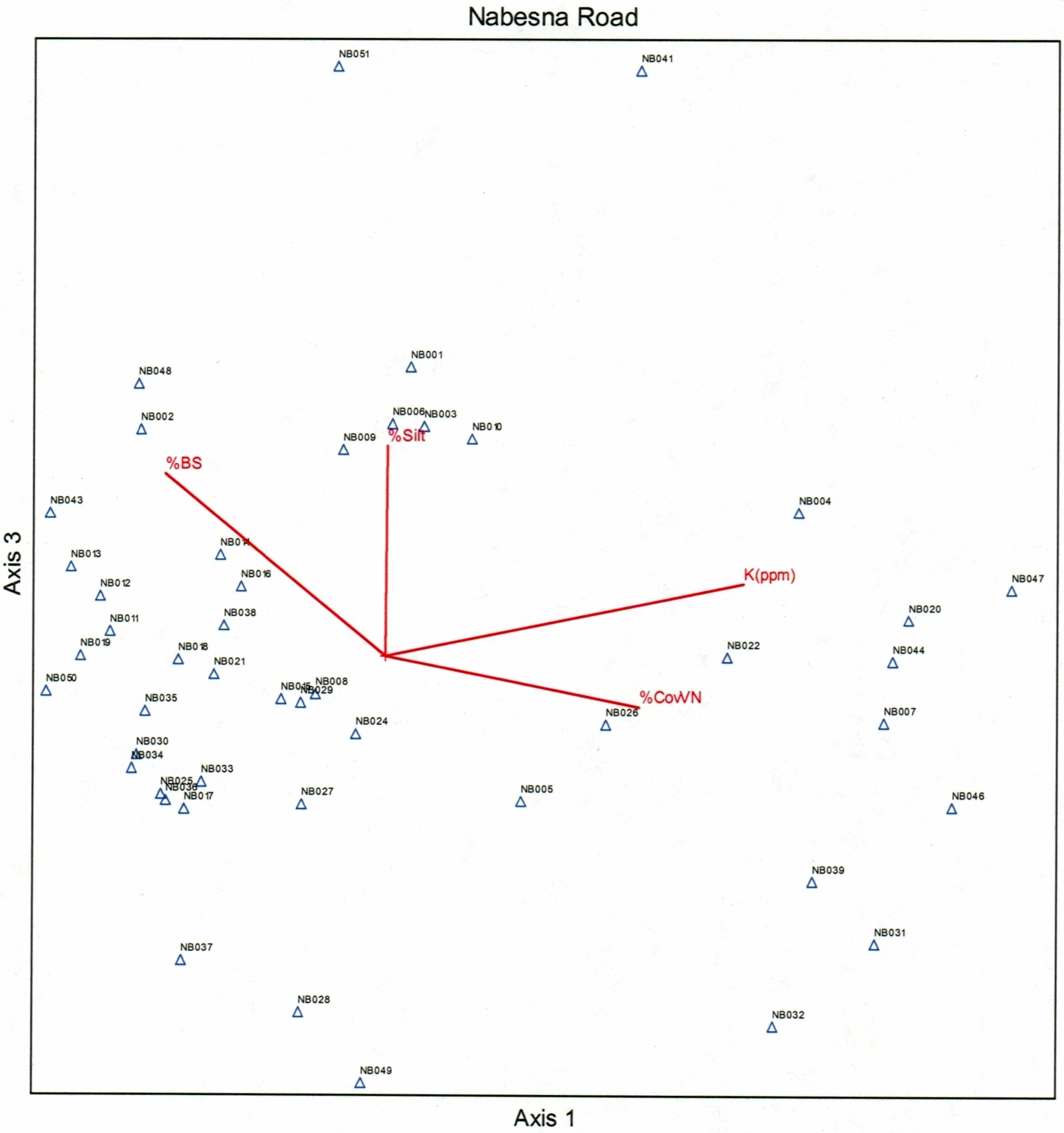

Figure 10. NMS ordination biplot for Nabesna Road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Table 5. Correlation coefficients of dominant matrix variables with ordination axes for McCarthy Road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer, 2003.

Variable	**Axis 1** r^2	**Axis 2** r^2	**Axis 3** r^2
% Cover Vascular Natives	.536	.113	.001
% Bare Soil	.510	.075	.132
Slope	.411	.025	.153
NH_4 (ppm)	.570	.002	.151
Phosphorus (ppm)	.437	.079	.066
Potassium (ppm)	.427	.297	.434

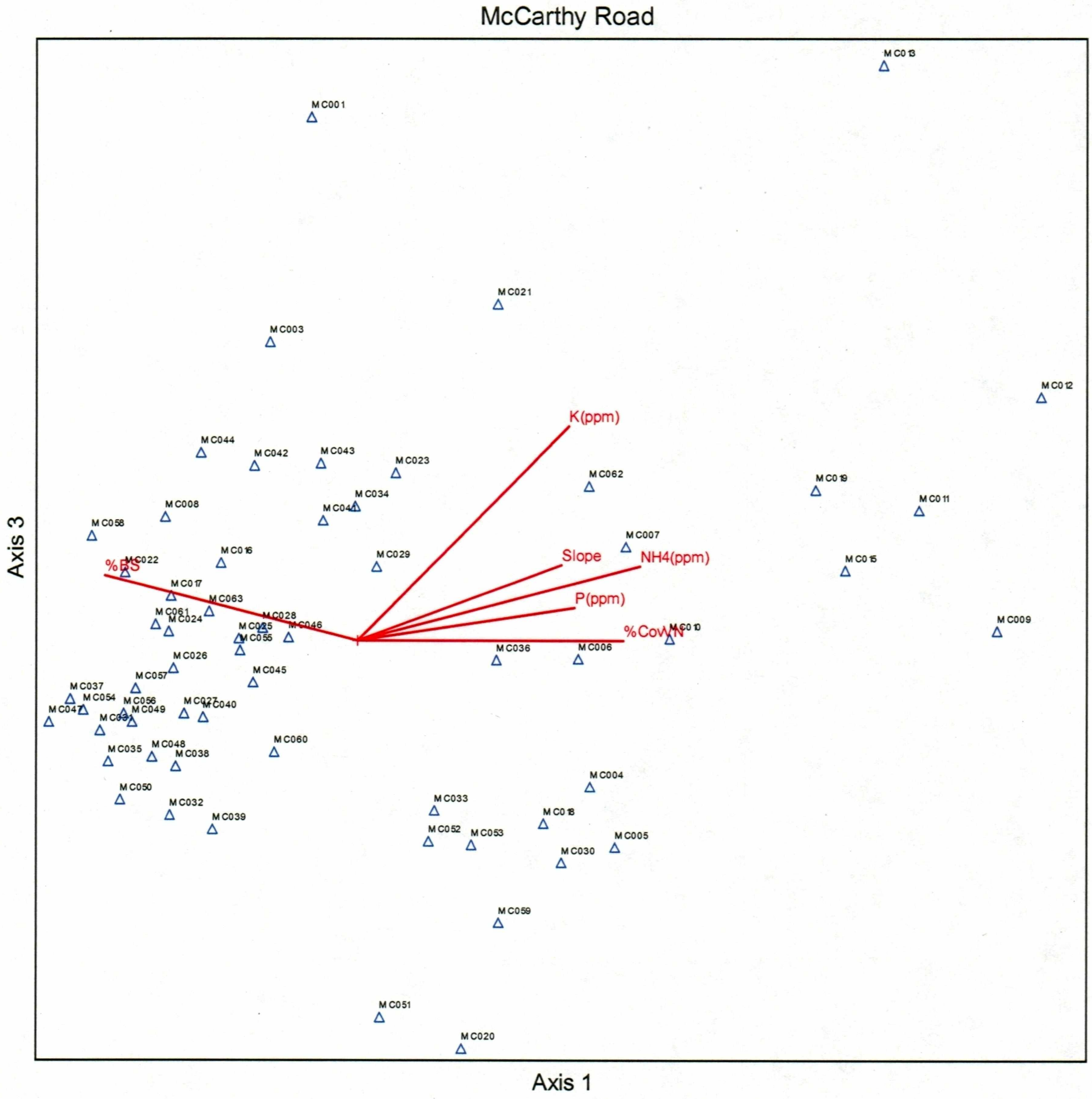

Figure 11. NMS ordination biplot for McCarthy Road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

percent cover litter (Table 6). Weaker associations were also evident for percent sand and percent silt. The ordination procedure eliminated 11 other environmental variables from the original data matrix for these sites. NMS ordination (Figure 12) represented 96% of the variation in the dataset, with 60% loaded on axis 1, and 27% on axis 2. Axis 3 explained little of the variation in this dataset and was excluded from further analysis.

For the cumulative data on trails ($n = 59$), plots were associated with percent cover exotics, phosphorus (ppm), potassium (ppm), and percent nitrogen (Table 7). The ordination procedure eliminated 11 other environmental variables from the original data matrix for these sites. NMS ordination (Figure 13) represented 90% of the variation in the dataset, with 62% loaded on axis 1, and 28% on axis 2.

Regression Analysis

When percent cover of exotic plants for each plot was regressed against the measured environmental variables found in each plot, percent cover litter, percent cover vascular natives, and percent bare soil were statistically significant ($r^2 = .78$, $p < .001$). Regression further reduced the number of important environmental variables from the five identified by NMS ordination. Interestingly, the variable percent cover litter was found to be significant, even though NMS showed it as having a weak association with the ordination axes.

For the Nabesna Road data, regression analysis revealed that percent bare soil, percent silt, and percent cover vascular natives were significant ($r^2 = .51$, $p < .001$). Regression reduced the number of important environmental variables to three from the

Table 6. Correlation coefficients of dominant matrix variables with ordination axes for road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Variable	**Axis 1** r^2	**Axis 2** r^2	**Axis 3** r^2
% Cover Exotic Species	.145	.431	.012
% Cover Vascular Natives	.453	.009	.216
% Bare Soil	.603	.543	.129
% Cover Litter	.393	.329	.068
Potassium (ppm)	.395	.520	.002

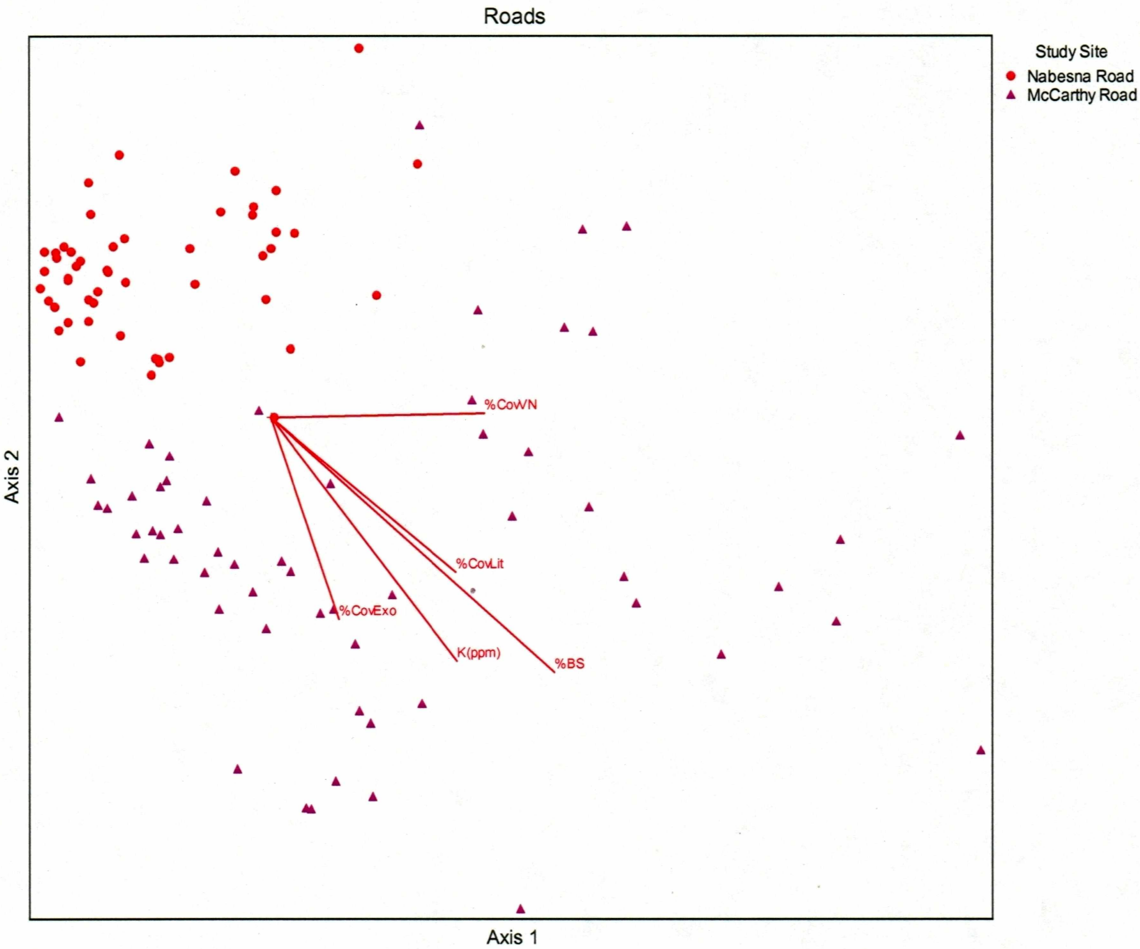

Figure 12. NMS ordination biplot for road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Table 7. Correlation coefficients of dominant matrix variables with ordination axes for trail plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

Variable	**Axis 1** $\mathbf{r^2}$	**Axis 2** $\mathbf{r^2}$
% Cover Exotic Species	.303	.287
Phosphorus (ppm)	.105	.758
Potassium (ppm)	.892	.000
% Nitrogen	.402	.001

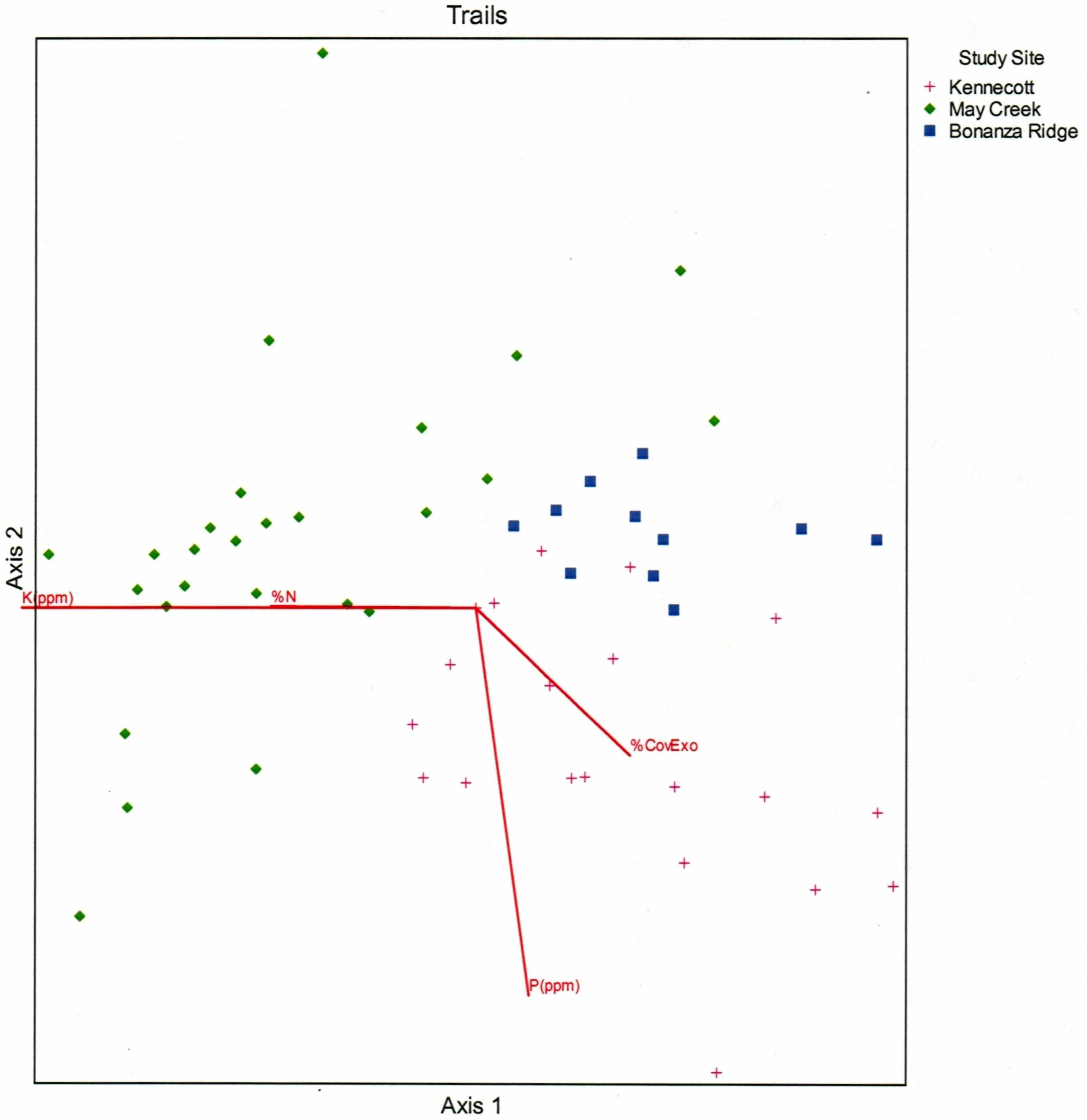

Figure 13. NMS ordination biplot for trail plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

four identified by NMS ordination. Although potassium was highly correlated with the first ordination axis, it was not statistically significant ($r^2 = .12$, $p = .98$).

For McCarthy Road, regression reduced the number of predictive variables from the six identified by NMS ordination. Significant variables were percent bare soil, slope, and percent cover vascular natives ($r^2 = .40$, $p < .001$). Although potassium, ammonium, and phosphorus correlated well with the first ordination axis, they were not statistically significant ($r^2 = .14$, $p > .05$).

For the cumulative road dataset, regression analysis reduced the number of predictive variables from the five identified by NMS ordination. Significant variables were percent cover litter, percent cover vascular natives, and percent bare soil ($r^2 = .95$, $p < .001$). As with previous sites, although potassium was highly associated with the first ordination axis, it was not statistically significant. In addition, although percent cover litter was not shown to be associated with any axis in the ordination, it was statistically significant in the regression model.

For the cumulative trails dataset, regression reduced the number of important variables down from the four identified by NMS ordination. Significant variables were potassium and phosphorus ($r^2 = .39$, $p < .001$). In this case, the variables most associated with ordination axes agreed with those shown to be statistically significant in the regression model.

A comparison of the mean percent cover of exotic species between roads and trails in WRST were carried out using the full dataset ($n = 173$). Mean percent cover of exotic species was not significantly different between roads ($\bar{x}$ = 14%) and trails ($\bar{x}$ = 18%) (t_{171} = -1.413, p = .16).

Cover of exotic species was compared between the Nabesna road ($\bar{x}$ = 10%) and the McCarthy road ($\bar{x}$ = 18%) (n = 114). Mean percent cover of exotics was significantly different between these two areas (t_{112} = -3.051, p = .003).

Comparison of mean exotic plant cover was also carried out between all pairs of trails in WRST. The data comparing trails in the Kennecott area ($\bar{x}$ = 32%) and May Creek ($\bar{x}$ = 6%) showed a significant difference in mean cover of exotic plants (t_{46} = 5.275, p <.001). Data comparing Bonanza Ridge trail ($\bar{x}$ = 25%) and trails in May Creek revealed a significant difference in the mean cover of exotic plants between these two areas as well (t_{37} = 3.529, p = .001). Comparison of mean exotic plant cover between Bonanza Ridge trail and Kennecott showed no significant difference (t_{29} = -.788, p = .43).

Discussion

Ordination and Regression Analysis

The ordination and regression analysis show that the invasion of WRST by exotic plants is still in the initial phases. Although sampling was limited to areas in which exotic plants were growing, the cover of exotic plants was not an important variable in explaining the variation in community composition. At every site other than the cumulative data on trails, the cover of vascular native species was consistently more important in explaining the variation in the ordination, and was a statistically significant variable in the regression. In addition, although exotic plants have been present in WRST for some time, exotic species richness is still very low in the park. Native plants represent the majority of plant cover and plant species richness, even in disturbed areas of WRST. However, exotic plants still pose a threat to the native plant communities of the park. The process of plant invasion has two distinct "lag" and "log phases" (Mack *et al.* 2000), and it is likely that exotic plant invasions in WRST are still in the lag phase. More often than not, the lag phase of invasion lasts for a long period, and the transition to the log phase of population growth may be dependent upon several factors including climatic changes, adaptive changes in life history characteristics of individual species, and the availability of safe sites for invading propagules (Kowarik 1995). WRST has several different forms of anthropogenic disturbances (roads, trails, backcountry cabins and airstrips, residential communities) providing a number of safe sites for the successful establishment of exotic species. In addition, percent bare soil was an important variable in the regression analysis, and can be seen as an analog to disturbance. Disturbance enhances the persistence of exotics by increasing the availability of one or more resources required for plant growth (Panetta and Hopkins 1991) and can lead to the invasion of these species into native vegetation by providing corridors into intact ecosystems (Fox and Fox 1986, Rejmanek 1989).

The significance of bare soil as a variable on both the Nabesna and McCarthy roads is not surprising given the large and varied types of disturbances common along these two corridors. Both roads have regular grading and additions of fill for maintenance purposes. The Nabesna road has several areas where wide, braided creeks cross, and the McCarthy road has areas where tree thinning is being carried out along the roadside in response to a bark beetle infestation. All of these activities can serve to loosen topsoil, eliminate the shading effects of canopy cover, and may also facilitate point sources of nutrient input, all of which can be conducive to the establishment and growth of exotic plant communities (Greenburg *et al.* 1997, Milton and Dean 1998, Parendes and Jones 2000).

The ordinations and regressions on roads reflect both the highly disturbed nature of these areas and the still dominant influence of native plant species. Percent cover of litter, percent bare soil and percent cover of vascular natives accounted for 95% of the variation of study plots within this disturbance type. Since disturbance is often seen as a precursor to weed invasion (Hobbs 1991), the roads in WRST will be likely sites for initial exotic plant invasions that could spread into more remote areas, especially as more people use these roads for access to backcountry areas of the park.

The dataset obtained for trails is unique among the other study sites in that the cover of vascular natives was not important in either the ordination axes or the statistical analysis. Percent cover of exotics was more highly associated with the ordination than were vascular natives, despite the fact that the cover of exotic plants at May Creek ($\bar{x}$ = 6%) was the lowest of any of the five study sites. This was also the only site where soil nutrients explained the greatest amount of variation in exotic plant cover in both the ordination and in the regression. The reasons for this discrepancy are not clear. The association of increased soil nutrient availability with increases in exotic plant cover and diversity has been well documented (Cale and Hobbs 1991, Pysek and Leps 1991) and is often tied to disturbance (Hobbs 1991, Williamson and Harrison 2002). The strongest correlation with cover of exotic plants was with phosphorus and potassium. This may be an indication that the naturally occurring levels of these nutrients may be limiting the growth of exotic plants in this area (Cale and Hobbs 1991). Phosphorus is often unavailable to plants due to its tendency to form complexes with calcium at high pH levels and with iron and aluminum at low pH levels. Why these soil nutrients are more closely tied to exotic plant growth on trails in WRST is uncertain.

Comparison of mean cover of exotics within and between sites has yielded some interesting results. There was a significant difference between the Nabesna and McCarthy roads and this may reflect differences in use levels, disturbances, and climatic conditions between these two sites. The McCarthy Road has an average daily traffic of 74 vehicles in the summer, while the Nabesna has 21 vehicles per day (Alaska Department of Transportation 2002). This is probably due to visitors using the McCarthy Road to access the town of McCarthy and the historic Kennecott mining area. Areas along the McCarthy road where tree thinning activities occurred had the highest levels of both exotic plant cover and diversity of any plots in this study. If use levels correspond to levels of disturbance, than it is not surprising that the McCarthy Road has more exotic plant coverage given the relationship between disturbance and the invasion and persistence of exotic plants (Hobbs 1991). Gradients of disturbance levels have been correlated with patterns of exotic plant growth in other areas (Parendes and Jones 2000). The climate of these two areas might also be a factor. The Nabesna road has more interior climatic conditions than the coastal environment of the McCarthy road (Gallant *et al.* 1995). There may be fewer frost free days and a shorter growing season on the more northern Nabesna road and this has been shown to be important with respect to the establishment and spread of exotic plants in other areas of the country (Chicoine *et al.* 1985). There was also a difference in the distribution and abundance of common dandelion (*T. officinale officinale*) between the two roads. While this exotic variety was widespread along the length of the McCarthy road, it was limited to only a dozen or so sites along the Nabesna. The more common dandelion in this area was the native variety (*T. officinale cerataphorum*), which was completely absent from the McCarthy road.

Comparison of exotic plant cover between roads and trails showed no significant difference between these two disturbance types. Since two of the three trails in this study were in areas easily accessible to people, there is probably little appreciable difference in the levels of use experienced between these disturbance types in WRST. The Bonanza Ridge trail and the trails in the Kennecott area had the highest cover of exotic plants among the five study sites (24% and 32% respectively) and although the May Creek area is more remote than the other study sites, there is substantial human activity in this area because of the presence of an NPS field station.

The data from trails also showed a significant difference in the mean cover of exotic plants between plots in Kennecott and May Creek, and between Bonanza Ridge and May Creek. The Bonanza Ridge trail and those in the Kennecott area are easily accessible by park visitors. May Creek is more remote and is not a tourist destination. Differences in use levels (and therefore disturbances) are probably responsible for this pattern. No significant difference in exotic plant cover was evident between plots along the Bonanza Ridge trail and those in Kennecott. This is not surprising given the close proximity of the Bonanza Ridge trail to Kennecott and the ease of access to these two areas. Interpretation of data from Bonanza Ridge must be viewed with caution, however, given the low sample sizes for this site (n = 11).

Throughout the analysis for each study site, percent cover of vascular natives, percent cover litter, and percent bare soil were often the most important variables in both the ordination and in the regression. Scatter plots for each of these variables for the full dataset show that all three are negatively correlated with the cover of exotic plant species (Figures 14-16). Since exotic plants are most often associated with areas of anthropogenic disturbance, one would expect that as disturbance increases, growth of exotic species would increase, while native plant species would be displaced and the amount of bare ground available for subsequent plant establishment would also decrease. In addition, since exotic species grow best in areas with little canopy or ground cover, as the amount of litter in a given area increases, the ability of exotics to grow in such conditions would decrease. This appears to be the case for my study.

Soils data revealed highly variable conditions between study sites with respect to the major soil nutrients. This was especially true for phosphorus and potassium. Plots at May Creek and Kennecott appear to be differentiated from one another based on these nutrients. The reasons for these differences are unknown. The only clear difference between the May Creek and Kennecott areas is the level of human use. The Kennecott area is easily accessible by road or hiking trail from the town of McCarthy. Indeed, it is the most frequently visited location in WRST. May Creek, however, is accessible only by fixed-wing aircraft and receives relatively little use by people, other than park service personnel who use the area as a remote field station during the summer months. How

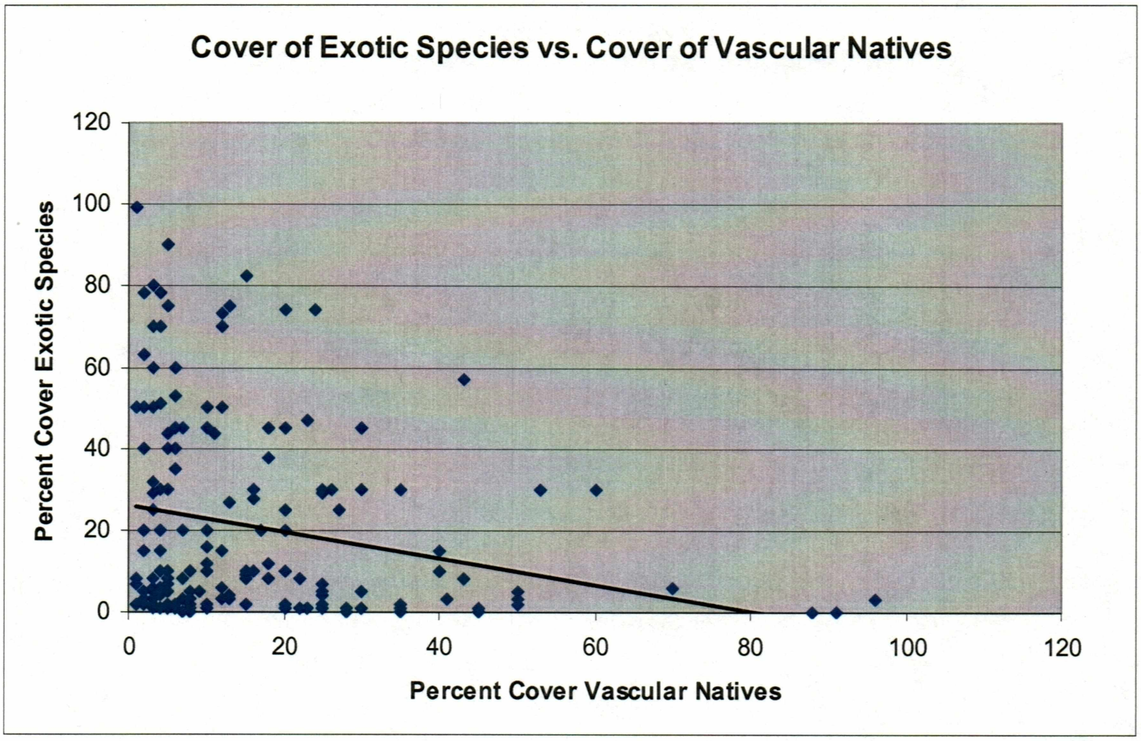

Figure 14. Relationship between cover of exotic species and cover of vascular natives for the full dataset, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

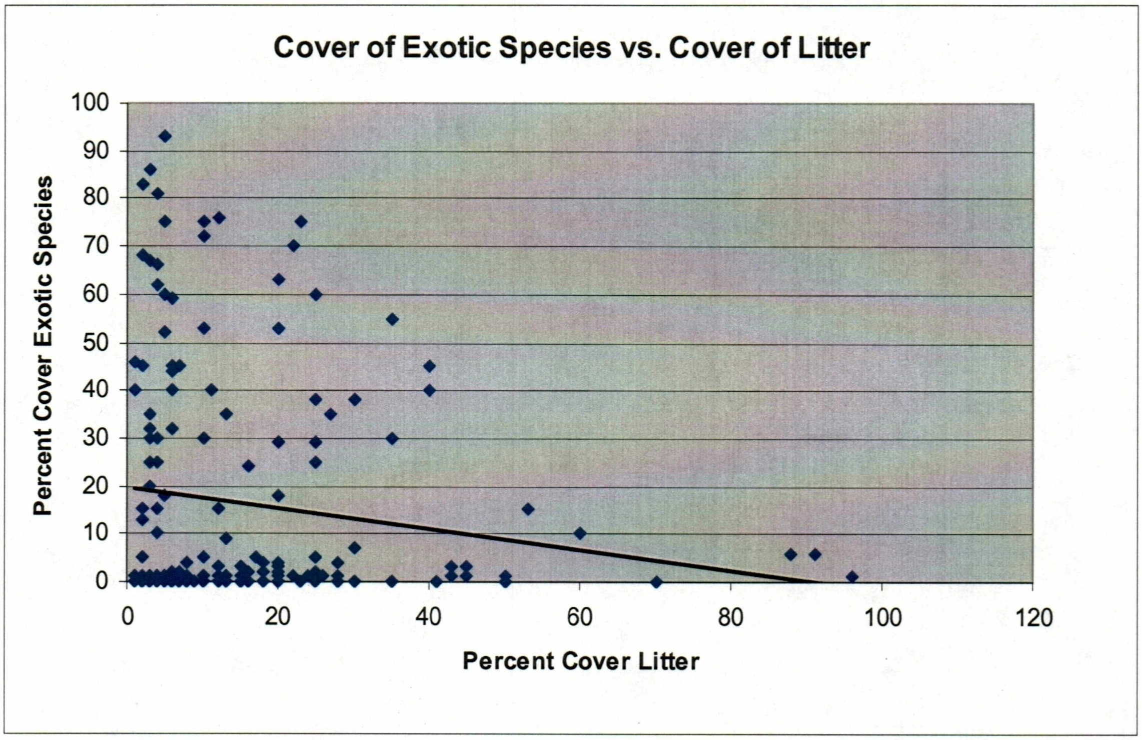

Figure 15. Relationship between cover of exotic species and cover of litter for the full dataset, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

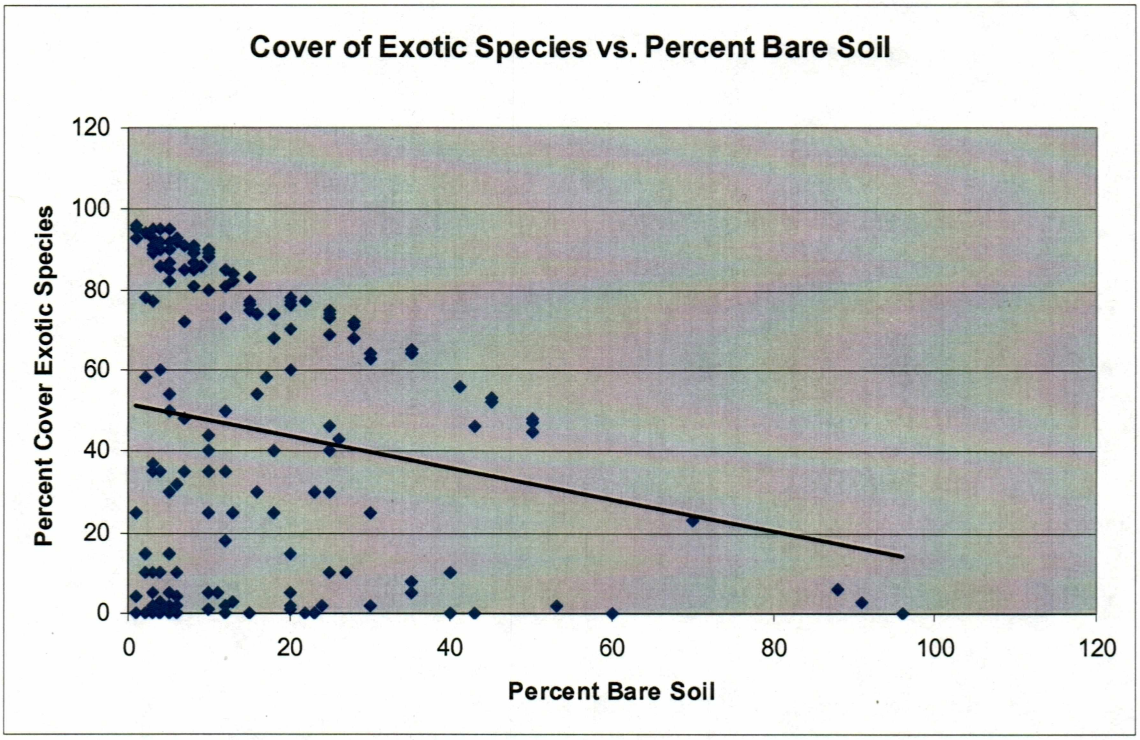

Figure 16. Relationship between cover of exotic species and percent of bare soil for the full dataset, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

levels of human use influence the amount of a given soil nutrient for an area is uncertain. This aspect of my research warrants further study.

Management Implications

Park management policies regarding exotics should be area and species specific. The remote areas of the park are still either devoid of exotic species or have very low levels of exotic growth and diversity. Any exotic plants found in these areas could be controlled through hand pulling. NPS staff responsible for the care and maintenance of backcountry cabins could be trained to identify the most common exotic species, and could pull any species encountered during visits to these sites. NPS field staff should also be trained to identify exotic plants as part of yearly seasonal training activities.

Not all exotic species warrant the same level of control and monitoring in WRST. Although the exotic dandelion, *T. officinale officinale*, is the most widespread exotic species in the park, eradication is unlikely. Even control of the species in some areas is not practical. It grows along the entire length of the McCarthy road and will probably continue to persist there given the high levels of disturbance present along this corridor. On the Nabesna road however, control and/or eradication is still possible. This species was restricted to just a few spots along the length of the road and could be the focus of concentrated control and monitoring efforts. Small pullouts, camping spots, and trailheads along the Nabesna Road should be closely monitored. Care should be taken to properly train park staff in the identification of both exotic and native varieties of dandelion as they were often found growing together in some areas.

Of more pressing concern along the Nabesna road is the presence of narrow-leaf hawksbeard, *Crepis tectorum*, and white sweetclover, *Melilotus alba*. Neither of these species was present on the Nabesna during initial surveys in 2000, but were found on the road in 2003. *C. tectorum* is an annual with deep taproots that can be difficult to completely remove. Once established in appreciable numbers, elimination of this species will prove difficult if not impossible. At this point, it is restricted to a small area at the Slana post office, but two specimens were found much further up the road at the Lost Creek trailhead (mile 31). White sweetclover has become established at the junction of the Nabesna road and the Tok cutoff. A large infestation is already thriving here and control efforts have already begun. This species is capable of nitrogen fixation and can invade areas of low nutrient availability. It has already invaded large areas along the Stikine River in southeast Alaska, and was found spreading down a trail to the Slana River near the border of WRST. The spread of this species should be the top priority in terms of control and eradication.

Along the McCarthy road, the establishment and spread of exotic plants is being facilitated by ongoing disturbances and revegetation efforts. All species of clover (*Trifolium spp.*), and smooth bromegrass (*Bromus inermis*) have been purposely seeded in some areas by the Alaska Department of Transportation (DOT) for purposes of erosion control. This practice should be eliminated, but is not directly under the control of WRST since the NPS does not have ownership of this corridor. Resource management staff at WRST should work closely with Alaska DOT to encourage the use of native species for revegetation efforts. The thinning of spruce trees along the McCarthy road should also be of concern to the park. Movement of logging equipment into the area could bring seeds of exotic species from other areas. Increases in incoming solar radiation with logging will create an environment conducive to the growth and spread of non-native species (Parendes and Jones 2000). This activity is taking place on native corporation land and therefore, not under the control of the NPS. Collaborative relationships between the native corporation and NPS resource staff should be encouraged. At a minimum, these areas should be monitored to ensure that more aggressive exotic species do not become established.

Since WRST is still in the initial phases of exotic plant invasion, the park has a unique opportunity to get a head start on prevention, eradication, and control efforts before the scope of the problem becomes overwhelming from a logistical and financial standpoint. Exotic plants are still limited to areas of anthropogenic disturbance in WRST, and use of park staff and funds for control efforts should be concentrated in these areas. Minimizing disturbance should be the top priority. Park resource management staff should work closely with maintenance personnel to make sure that park activities are minimizing the scope and degree of disturbances in the more popular areas of the park. Road, trail, and infrastructure maintenance activities should be viewed as long-term ecological processes, rather than short term engineering projects (Tyser and Worley 1992). Cooperative efforts between the NPS and other agencies (native corporations, Alaska DOT) should be encouraged if the long-term prevention and control of exotic plants in WRST is to be successful.

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Appendix 1. Locations of exotic plants in Wrangell-St. Elias National Park and Preserve, Alaska, Summer, 2003.

Site Code*	Species Present**	Latitude	Longitude
BR001	TAROFF	61.4881636	-142.8900921
BR002	TAROFF	61.4876099	-142.8873398
BR003	TAROFF	61.4880800	-142.8869655
BR004	TAROFF	61.4916085	-142.8832871
BR005	TAROFF	61.4919518	-142.8812521
BR006	TAROFF	61.4917049	-142.8789598
BR007	TAROFF	61.4914785	-142.8768715
BR008	TAROFF	61.4907338	-142.8752771
BR009	TAROFF	61.4946245	-142.8723245
BR010	TAROFF	61.4942298	-142.8707691
BR011	TAROFF	61.4959065	-142.8643770
BR012	TAROFF	61.4985980	-142.8616227
BR013	TAROFF	61.4842145	-142.8877971
KN001	TAROFF	61.4868663	-142.8904980
KN002	TAROFF	61.4867351	-142.8903892
KN003	TAROFF, TRIHYB	61.4859536	-142.8894494
KN004	TAROFF	61.4848430	-142.8885317
KN005	TAROFF, TRIHYB, TRIREP	61.4847770	-142.8881879
KN006	TAROFF	61.4840011	-142.8877435
KN007	TAROFF, TRIHYB	61.4835218	-142.8874638
KN008	TAROFF	61.4828211	-142.8868077
KN009	TAROFF	61.4826326	-142.8866824
KN010	TAROFF	61.4819371	-142.8859392
KN011	TAROFF, TRIHYB	61.4815215	-142.8854903
KN012	TAROFF	61.4833163	-142.8870491
KN013	TAROFF, TRIHYB	61.4828123	-142.8863064
KN014	TAROFF	61.4821407	-142.8853306
KN015	TAROFF, TRIHYB	61.4853159	-142.8850032
KN016	TAROFF, PLAMAJ	61.4865188	-142.8871598
KN017	TRIHYB, TRIPRA	61.4804480	-142.8854718
KN018	MATDIS, TRIHYB, POLAVI	61.4802887	-142.8848837
KN019	LEUVUL	61.4817319	-142.8865653
KN020	LEUVUL	61.4815989	-142.8864173
MC001	CRETEC	61.5363580	-144.3759822
MC002	TAROFF	61.5213221	-144.3328130
MC003	LAPSQU, POLAVI, TAROFF	61.5214664	-144.3320566
MC004	BROINE	61.5219378	-144.3287919
MC005	PLAMAJ	61.5225319	-144.3139000
MC006	PLAMAJ	61.5260967	-144.3086027
MC007	TAROFF, PLAMAJ	61.5264212	-144.3079125
MC008	PLAMAJ	61.5276439	-144.3013135
MC009	TAROFF	61.5259758	-144.2942505
MC010	CRETEC, CHEALB, POLAVI	61.5216805	-144.2840875
MC011	POLAVI, LEPDEN, CHEALB, LAPSQU	61.5214034	-144.2828048

Appendix 1 Continued

Site Code*	**Species Present****	**Latitude**	**Longitude**
MC012	TAROFF, LEPDEN, CHEALB, LAPSQU	61.5209064	-144.2804696
MC013	CHEALB, LEPDEN	61.5206854	-144.2753156
MC014	LEPDEN, CHEALB, LAPSQU	61.5206590	-144.2753156
MC015	TAROFF	61.5224720	-144.2566305
MC016	PLAMAJ, TAROFF	61.5219440	-144.2469834
MC017	PLAMAJ	61.5224390	-144.2244524
MC018	PLAMAJ	61.5202827	-144.1965948
MC019	TRIHYB	61.5194138	-144.1809279
MC020	TAROFF, PLAMAJ, TRIHYB	61.5252809	-144.1512948
MC021	TAROFF	61.4920237	-144.0208589
MC022	TRIHYB, BROINE	61.4870911	-144.0167890
MC023	TAROFF	61.4811372	-144.0086291
MC024	TAROFF	61.4765320	-144.0055190
MC025	TAROFF	61.4741966	-143.9904411
MC026	TAROFF, PLAMAJ	61.4726816	-143.9781139
MC027	TAROFF	61.4675997	-143.9371606
MC028	TAROFF	61.4692471	-143.9294887
MC029	TAROFF	614634516	-143.8668653
MC030	TAROFF	61.4620586	-143.8646789
MC031	TAROFF, LAPSQU	61.4619002	-143.8551999
MC032	TRIHYB	61.4509760	-143.7562269
MC033	TAROFF, PLAMAJ	61.4423746	-143.7380292
MC034	TAROFF	61.4377131	-143.7287822
MC035	TAROFF, TRIHYB	61.3912876	-143.6522492
MC036	TAROFF	61.3632275	-143.5257334
MC037	LAPSQU, TRIHYB	61.3626488	-143.4997143
MC038	TRIHYB	61.3626402	-143.4985326
MC039	TAROFF	61.3632322	-143.4817678
MC040	TAROFF, TRIHYB	61.3652005	-143.4446403
MC041	TAROFF, TRIHYB, PLAMAJ	61.3666818	-143.4301590
MC042	TAROFF	61.3713855	-143.3733051
MC043	TAROFF	61.3742458	-143.3510325
MC044	BROINE	61.3866156	-143.2454038
MC045	BROINE, TRIHYB	61.3869797	-143.2446596
MC046	BROINE, TRIHYB	61.3870329	-143.2387648
MC047	TAROFF, PLAMAJ	61.3871082	-143.1743514
MC048	TAROFF	61.3949019	-143.1550954
MC049	TAROFF, PLAMAJ	61.3952475	-143.1540899
MC050	PLAMAJ	61.3992221	-143.1402349
MC051	TAROFF	61.3997963	-143.1359173
MC052	TAROFF	61.4012678	-143.1281941
MC053	TAROFF	61.4011403	-143.1246034

Appendix 1 Continued

Site Code*	Species Present**	Latitude	Longitude
MC054	TAROFF	61.4039763	-143.1010082
MC055	TAROFF	61.4044653	-143.0918561
MC056	TAROFF	61.4041804	-143.0760075
MC057	TAROFF	61.4082657	-143.0584447
MC058	TAROFF	61.4153295	-143.0182403
MC059	TAROFF	61.4187795	-143.0093642
MC060	TAROFF, ELYREP	61.4270129	-142.9911577
MC061	TAROFF	61.4361343	-142.9653909
MC062	TAROFF	61.4358994	-142.9620278
MC063	TAROFF	61.4340782	-142.9463991
NB001	PLAMAJ	62.7106711	-143.9838365
NB002	MATDIS	62.7109417	-143.9843207
NB003	PLAMAJ	62.6923937	-143.9121198
NB004	PLAMAJ, ACHMIL	62.6883734	-143.9068423
NB005	PLAMAJ	62.6875749	-143.9042183
NB006	PLAMAJ	62.6757127	-143.8783656
NB007	PLAMAJ	62.6756679	-143.8780168
NB008	PLAMAJ, TAROFF	62.6404986	-143.7720352
NB009	PLAMAJ, ACHMIL	62.6321355	-143.7409559
NB010	TAROFF, ACHMIL	62.6234057	-143.7130881
NB011	TAROFF	62.6222437	-143.7062328
NB012	PLAMAJ	62.6213093	-143.7029281
NB013	PLAMAJ, TAROFF, ACHMIL	62.6211605	-143.7024272
NB014	ACHMIL, PLAMAJ	62.6153215	-143.6786336
NB015	PLAMAJ, ACHMIL	62.6138695	-143.6749955
NB016	PLAMAJ, ACHMIL	62.6137268	-143.6748896
NB017	TAROFF, PLAMAJ, MATDIS	62.6006357	-143.6197284
NB018	PLAMAJ	62.5748861	-143.5277289
NB019	PLAMAJ	62.5714757	-143.5036839
NB020	PLAMAJ, ACHMIL	62.5636546	-143.4168834
NB021	PLAMAJ, MATDIS	62.5639500	-143.4166687
NB022	PLAMAJ	62.5638521	-143.4169621
NB023	PLAMAJ, MATDIS	62.5632132	-143.4131699
NB024	PLAMAJ	62.5625222	-143.4132265
NB025	TAROFF	62.5538950	-143.3959776
NB026	TAROFF, ACHMIL, PLAMAJ	62.5484380	-143.3643154
NB027	TAROFF	62.5486771	-143.3548786
NB028	PLAMAJ	62.5443703	-143.3262802
NB029	TAROFF	62.5314130	-143.2806961
NB030	TAROFF	62.5303949	-143.2782079
NB031	DESSOP, ACHMIL	62.5295451	-143.2531031
NB032	DESSOP	62.5293965	-143.2524634
NB033	TAROFF	62.5209495	-143.2147518
NB034	TAROFF	62.5200784	-143.2107511

Appendix 1 Continued

Site Code*	Species Present**	Latitude	Longitude
NB035	TAROFF	62.5190518	-143.2057913
NB036	TAROFF	62.5190748	-143.2026591
NB037	TAROFF	62.5134200	-143.1698014
NB038	TAROFF	62.5127912	-143.1696366
NB039	TAROFF	62.5015496	-143.1558855
NB040	TAROFF	62.4103490	-143.0038191
NB041	CRETEC, TAROFF, PLAMAJ	62.7066032	-143.9697521
NB042	PLAMAJ	62.3705268	-143.0104033
NB043	DESSOP	62.3717194	-143.0067325
NB044	PLAMAJ	62.3757161	-143.0011988
NB045	PLAMAJ	62.3854485	-143.0000133
NB046	PLAMAJ	62.3936131	-142.9991948
NB047	PLAMAJ	62.3946245	-142.9945524
NB048	DESSOP	62.5109477	-143.1644766
NB049	MATDIS	62.5764872	-143.5351453
NB050	MATDIS	62.5936675	-143.5927134
NB051	MELALB	62.7130047	-143.9878318
MYC001	TAROFF	61.3478050	-142.7059360
MYC002	TAROFF	61.3477893	-142.7055943
MYC003	TAROFF	61.3480258	-142.7054444
MYC004	TAROFF	61.3477759	-142.7063830
MYC005	TAROFF	61.3476124	-142.7068021
MYC006	TAROFF, PLAMAJ	61.3476400	-142.7072039
MYC007	TAROFF, PLAMAJ	61.3472247	-142.7085756
MYC008	TAROFF	61.3470752	-142.7136966
MYC009	TAROFF, TRIHYB	61.3468777	-142.7157139
MYC010	TAROFF, PLAMAJ	61.3485056	-142.7263991
MYC011	TAROFF	61.3450681	-142.7192160
MYC012	TAROFF	61.3310982	-142.6801179
MYC013	TAROFF	61.3343362	-142.6835447
MYC014	TAROFF	61.3375026	-142.6871250
MYC015	TAROFF	61.3406276	-142.6908042
MYC016	TAROFF	61.3227091	-142.6643996
MYC017	TAROFF, TRIHYB	61.3253406	-142.6702446
MYC018	TAROFF, PLAMAJ	61.3271688	-142.6724707
MYC019	TAROFF, PLAMAJ	61.3304663	-142.6798137
MYC020	TAROFF	61.3426174	-142.6925349
MYC021	TAROFF, PLAMAJ, TRIREP	61.3474244	-142.7015119
MYC022	TRIHYB	61.3474633	-142.6981822
MYC023	TAROFF	61.3656850	-142.6961312
MYC024	TRIREP	61.3578514	-142.6982630
MYC025	PLAMAJ	61.3511460	-142.6966683
MYC026	TAROFF	61.3326793	-142.6823861
MYC027	TAROFF	61.3359530	-142.6858695

Appendix 1 Continued

Site Code*	Species Present**	Latitude	Longitude
MYC028	TAROFF	61.3391856	-142.6890263

*See Appendix 2 for Site Codes
**See Appendix 3 for Plant Codes

Appendix 2. Site Codes for sample sites in Wrangell-St. Elias National Park and Preserve, Alaska, Summer, 2003.

Site Name	**Site Code**
Bonanza Ridge Trail	BR
Kennicott Mine	KN
McCarthy Road	MC
May Creek Area	MYC
Nabesna Road	NB

Appendix 3. Exotic plant list for Wrangell-St. Elias National Park and Preserve, Alaska, Summer, 2003.

Plant Name	**Common Name**	**PlantCode**
Achillea millefolium	Common Yarrow	ACHMIL
Bromus inermis	Smooth Brome Grass	BROINE
Chenopodium album	Pigweeed	CHEALB
Crepis tectorum	Narrow Leaf Hawksbeard	CRETEC
Descurania sophia	Tansy Mustard	DESSOP
Elymus repens	Quackgrass	ELYREP
Lappula squarrosa	Bluebur	LAPSQU
Lepidium densiflorum	Common Peppergrass	LEPDEN
Leucanthemum vulgare	Ox-eye Daisy	LEUVUL
Matricaria discoidea	Pineapple Weed	MATDIS
Melilotus alba	White Sweet Clover	MELALB
Plantago major	Common Plantain	PLAMAJ
Polygonum aviculare	Prostrate Knotweed	POLAVI
Taraxacum officinale officinale	Common Dandelion	TAROFF
Trifolium hybridum	Alsike Clover	TRIHYB
Trifolium repens	White Clover	TRIREP
Trifolium pratense	Red Clover	TRIPRA

Appendix 4. Results of Monte Carlo test and stress of the full dataset, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

STRESS IN RELATION TO DIMENSIONALITY (Number of Axes)

	Stress in real data 10 run(s)			Stress in randomized data Monte Carlo test, 20 runs			
Axes	Minimum	Mean	Maximum	Minimum	Mean	Maximum	p
1	32.064	45.126	57.385	42.015	48.833	57.380	0.0476
2	17.967	18.747	20.149	22.373	24.328	26.397	0.0476
3	11.029	11.195	12.086	15.636	16.368	17.671	0.0476
4	7.860	7.989	8.758	12.262	12.696	13.599	0.0476
5	6.523	6.607	6.813	9.908	10.157	10.621	0.0476
6	5.659	5.743	6.047	8.184	8.384	8.771	0.0476

p = proportion of randomized runs with stress < or = observed stress
i.e., p = (1 + no. permutations <= observed)/(1 + no. permutations)

Conclusion: a 3-dimensional solution is recommended.

Appendix 5. Results of Monte Carlo test and stress for Nabesna Road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

STRESS IN RELATION TO DIMENSIONALITY (Number of Axes)

	Stress in real data 10 run(s)			Stress in randomized data Monte Carlo test, 20 runs			
Axes	Minimum	Mean	Maximum	Minimum	Mean	Maximum	p
1	31.592	47.315	56.493	31.160	45.659	56.490	0.0952
2	17.507	18.289	20.564	18.988	20.838	23.904	0.0476
3	10.930	11.625	12.637	12.236	13.516	14.970	0.0476
4	7.305	7.723	8.610	8.770	9.722	11.419	0.0476
5	5.878	5.947	6.167	6.795	7.603	8.306	0.0476
6	4.734	4.807	5.112	5.751	6.220	6.976	0.0476

p = proportion of randomized runs with stress < or = observed stress
i.e., p = (1 + no. permutations <= observed)/(1 + no. permutations)

Conclusion: a 3-dimensional solution is recommended.

Appendix 6. Results of Monte Carlo test and stress for McCarthy Road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

STRESS IN RELATION TO DIMENSIONALITY (Number of Axes)

	Stress in real data 10 run(s)			Stress in randomized data Monte Carlo test, 20 runs			
Axes	Minimum	Mean	Maximum	Minimum	Mean	Maximum	p
1	32.807	40.088	56.711	39.630	48.213	56.714	0.0476
2	18.371	19.242	20.638	21.972	23.656	28.929	0.0476
3	10.206	10.206	10.206	14.783	15.885	16.804	0.0476
4	7.774	7.900	8.192	10.867	11.645	12.095	0.0476
5	6.264	6.333	6.458	8.499	8.974	9.591	0.0476
6	5.105	5.157	5.308	6.798	7.214	7.842	0.0476

p = proportion of randomized runs with stress < or = observed stress
i.e., p = (1 + no. permutations <= observed)/(1 + no. permutations)

Conclusion: a 3-dimensional solution is recommended.

Appendix 7. Results of Monte Carlo test and stress of plots in the Kennecott Mine area, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

STRESS IN RELATION TO DIMENSIONALITY (Number of Axes)

	Stress in real data 10 run(s)			Stress in randomized data Monte Carlo test, 20 runs			
Axes	Minimum	Mean	Maximum	Minimum	Mean	Maximum	p
1	31.508	44.187	54.394	35.197	47.418	54.351	0.0476
2	14.957	16.210	18.076	14.690	19.828	26.550	0.0952
3	8.373	8.434	8.460	8.857	11.242	13.769	0.0476
4	5.261	5.411	5.761	5.430	6.978	9.329	0.0476
5	3.495	3.496	3.499	3.712	5.195	17.082	0.0476
6	2.442	2.622	2.773	2.283	3.153	4.163	0.1429

p = proportion of randomized runs with stress < or = observed stress
i.e., p = (1 + no. permutations <= observed)/(1 + no. permutations)

Conclusion: a 3-dimensional solution is recommended.

Appendix 8. Results of Monte Carlo test and stress of plots in the May Creek area, Wrangell-St.Elias National Park and Preserve, Alaska, Summer 2003.

STRESS IN RELATION TO DIMENSIONALITY (Number of Axes)

	Stress in real data 10 run(s)			Stress in randomized data Monte Carlo test, 20 runs		
Axes	Minimum	Mean	Maximum	Minimum	Mean	Maximum	p
1	24.237	46.757	55.342	21.199	39.040	55.131	0.0952
2	8.766	11.721	16.317	13.122	16.802	19.601	0.0476
3	5.374	5.497	6.604	7.911	10.199	12.289	0.0476
4	4.231	4.349	4.471	5.826	7.077	9.108	0.0476
5	3.381	3.521	3.754	4.315	5.163	6.321	0.0476
6	2.610	2.800	3.013	3.225	3.846	4.351	0.0476

p = proportion of randomized runs with stress < or = observed stress
i.e., p = (1 + no. permutations <= observed)/(1 + no. permutations)

Conclusion: a 2-dimensional solution is recommended.

Appendix 9. Results of Monte Carlo test and stress of road plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

STRESS IN RELATION TO DIMENSIONALITY (Number of Axes)

	Stress in real data 10 run(s)			Stress in randomized data Monte Carlo test, 20 runs			
Axes	Minimum	Mean	Maximum	Minimum	Mean	Maximum	p
1	29.080	40.583	57.185	43.465	47.663	51.101	0.0476
2	14.539	15.663	16.906	22.863	24.100	25.477	0.0476
3	8.756	8.767	8.776	15.138	16.443	18.185	0.0476
4	6.872	7.094	7.280	11.459	12.467	13.500	0.0476
5	5.868	5.950	6.137	9.326	9.952	10.898	0.0476
6	5.040	5.343	7.349	7.903	8.268	9.219	0.0476

p = proportion of randomized runs with stress < or = observed stress
i.e., p = (1 + no. permutations <= observed)/(1 + no. permutations)

Conclusion: a 3-dimensional solution is recommended.

Appendix 10. Results of Monte Carlo test and stress of trail plots, Wrangell-St. Elias National Park and Preserve, Alaska, Summer 2003.

STRESS IN RELATION TO DIMENSIONALITY (Number of Axes)

	Stress in real data 10 run(s)			Stress in randomized data Monte Carlo test, 20 runs			
Axes	Minimum	Mean	Maximum	Minimum	Mean	Maximum	p
1	27.525	41.112	56.212	32.847	47.508	56.438	0.0476
2	13.402	15.166	18.054	15.327	18.717	25.738	0.0476
3	9.093	9.171	9.418	10.417	12.638	14.417	0.0476
4	6.111	6.121	6.178	8.254	9.281	10.282	0.0476
5	4.824	4.869	5.230	6.231	7.217	8.052	0.0476
6	3.984	4.023	4.126	5.259	5.837	6.345	0.0476

p = proportion of randomized runs with stress < or = observed stress
i.e., p = (1 + no. permutations <= observed)/(1 + no. permutations)

Conclusion: a 2-dimensional solution is recommended.